Chapter 4
Augmented Reality

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Abstract

Much of the visualization in image-guided interventions is achieved by creating a virtual image of the surgical or therapeutic environment, based upon preoperative images, and displaying it on a workstation that is remote from the patient. Linkages between the patient and the image are created through image registration and tracked tools. Such solutions are not always ideal, and result in a psychophysical decoupling of the actual and virtual therapeutic working spaces. Using augmented reality, these two spaces are fused into a single volume, which is typically viewed stereoscopically so that a preoperative or intraoperative patient image appears at the location of the actual patient anatomy. The surgeon has the perception that he is "seeing through" the patient or organ surface to observe the operative site. This chapter reviews the various approaches to augmented reality, and discusses the engineering and psychophysical challenges in developing user-friendly systems.

4.1 Introduction

4.1.1 What Is Augmented Reality?

Augmented reality (AR) is a visualization concept that enhances real images with virtual, computer-generated graphics. The term mixed reality is often used to describe the whole spectrum that ranges from AR, where the emphasis is on the real image, to augmented virtuality, where the virtual scene dominates and the real elements appear as add-ons [Milgram and Kishino 1994].

Interestingly, the general concept of enhancing real images with computer graphics is already ubiquitous in today's media. A photo with text annotation may be regarded as one, albeit very simple, example. Weather reports on TV go further and use blue screen technology to make a real

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weather person appear in front of computer-generated weather maps. And, of course, all Hollywood action movies nowadays rely on a sophisticated combination of real shots with computer-generated imagery.

In contrast to these everyday examples, the concept of combining real and virtual images still needs to be established in medical practice. In this chapter, we want to put forward a specific understanding of medical AR as an advanced form of interventional image guidance. Based on that understanding, medical AR has very specific requirements.

For medical AR, it is useful to consider medical images as maps of a patient's anatomy. Instead of displaying these maps apart from the patient as in standard medical navigation systems, we overlay them directly onto the physician's view of the real patient. If, for example, there is a tumor in the map, we perceive this tumor now as a graphical object at the location of the actual tumor. Figure 4.1 illustrates this basic principle.

Fig. 4.1. *Left*: A cross-sectional CT image of a "patient." *Right*: Augmented view of the patient with the CT image appearing at the location of the actual anatomy (figures are from Sauer et al. 2000, © 2000 IEEE)

A central requirement for medical AR in the field of image guidance is precise registration between the map and the corresponding real patient. If the map does not align correctly with the patient, AR can become dangerous, as the physician would be guided to place instruments in incorrect locations. Furthermore, medical AR needs to be "on-line," which means it must be available in real time to the physician, who is acting on the information when performing a surgical or interventional procedure.

Figure 4.2 lists the components of a typical medical AR view. On the "real" side, we have an optical or video view of patient and instruments (and sometimes the physician's hands). On the "virtual" side, we have graphical models of the patient (the anatomical map), derived from a preoperative image (e.g., CT) or provided by a real-time modality (e.g., ultrasound), and models of surgical instruments and treatment plans.

To include virtual views of the surgical instruments, the locations of these instruments need to be tracked in the same way as for standard navigation systems. Treatment plans are optional and can be inserted as annotations in the patient map. A treatment plan shows, for example, entry point and path for a needle procedure, or shape and size of resection volume for a tumor operation. The AR view is then created as a fusion of the real view with a rendering of the virtual components.

▪ Patient ▪ Instruments	▪ Models (maps) of patient ▪ Models of instruments ▪ Models of treatment plans

Fig. 4.2. Real and virtual components of medical AR visualization

4.1.2 Why AR for Interventional Guidance?

In general, image guidance systems help the physician to establish a correspondence between locations in a patient's medical images (the "patient map") and the patient's physical body.

In conventional image guidance systems, a pointer or an instrument is tracked and the location visualized in the medical images. The physician observes on a monitor where the pointer or the instrument is positioned with respect to the internal anatomical structures. Hence, the conventional image guidance system maps the instrument into the medical data set, and displays the relationship on a monitor separate from the patient.

In contrast, image guidance that incorporates AR places the patient map directly in the 3D context of the patient's body. AR visualization enables the physician to focus on the surgical site without dividing his attention between the patient and a separate monitor. AR visualization can facilitate hand-eye coordination as the physician observes real and virtual instruments from a consistent natural point-of-view. Furthermore, with stereoscopic AR visualization, the relationships between 3D anatomical structures and the patient are readily appreciated.

The conceptual advantages of AR have to be realized in a practical way. The next section describes a number of design options for building an AR system.

4.2 Technology Building Blocks and System Options

To generate an AR view, we can either combine the computer graphics with a direct view of the real scene in an optical manner, or with a video view electronically. This leads to a very fundamental distinction between AR systems. We call the former category of systems optical AR systems, the latter video AR systems. This nomenclature is most common when using head-mounted displays; here one distinguishes between optical see-through and video see-through systems. A special case of video AR systems is the endoscopic video system that overlays medical graphics onto the endoscopic video images.

Video systems always contain an optical system: the lenses in front of the video sensor. This results in a real image that is not well characterized and independent of the user. The same is true with an optical microscope system that contains a well-defined optical axis to which the user keeps his eye aligned. However, if one looks into the real world through a semitransparent screen that displays the virtual image, one experiences a viewpoint-dependent parallax shift between these two images. Both the screen and the user need to be tracked in this case to keep real and virtual images correctly aligned. Hence, a further important distinction is between AR systems that have an optical axis and those that do not.

Another distinction arises from the configuration and placement of the displays, affecting the ergonomics and usability of the system. An important basic difference is whether the user wears the displays in a head-mounted fashion, or whether the displays are attached to an external mount. A stereoscopic system, in contrast to a monoscopic system, provides the user with a 3D perception of the AR scene.

Figure 4.3 lists these basic design options for AR systems. In Section 4.4, we will use them to organize our overview of the systems that have been described in the literature.

Optical	■	Video
Screen without optical axis	■	System with optical axis
Head mount	■	External mount
Mono	■	Stereo

Fig. 4.3. Important AR system design options

In the same way that tracking is an essential enabling technology for standard image guidance systems, we need tracking for AR image guidance. For AR, we not only must keep track of where the instruments may be positioned with respect to the patient, but more importantly we also must know the user's viewpoint, that is the viewpoint and viewing direction that determines how the patient is seen in the real view.

Based on this information of real viewpoint and viewing direction, we can place a virtual camera in the corresponding pose relative to the patient model (external camera parameters), and render the virtual image accordingly, making use of the internal camera parameters determined in a prior calibration step. If the patient model has been correctly registered to the real patient, the AR view will show the graphics view of the patient model in correct alignment with the real view of the patient.

Calibration and registration methods vary with different AR systems configuration. Sauer et al. [2000] and Vogt et al. [2006] describe the case of a video see-through system. Tuceryan and Navab [2000] present a calibration method for an optical see-through system.

4.3 System Examples and Applications

A relatively small number of groups have been active in developing AR systems for medical navigation. The credit for the first medical AR publication goes to Bajura et al. [1992], who describe the idea of overlaying live ultrasound images onto a live view of a patient using a head-mounted display.

In this section, we present an overview of the AR systems literature. This is not organized historically, but follows the design structure displayed in Fig. 4.3. The following survey describes examples of systems and applications that are based on optical microscopes (optical AR with optical axis), video-based technologies, large semitransparent screens (optical AR without optical axis), tomographic overlays as a special case of large-screen systems, and endoscopy (a special case of video based systems). We also briefly mention some methods that go beyond these AR approaches.

Applications targeted by AR systems include neurosurgery and otolaryngology, cranio- and maxillofacial surgery, breast and abdominal needle biopsies and tumor ablations, orthopedics, and cardiovascular and thoracic surgery.

After the examples in this section, we will list characteristic features of the different system types in Section 4.5 for an easier comparison.

4.3.1 Optical Microscope Systems

Operating microscopes are routinely used for many ENT and neuro-surgical procedures. AR image guidance can be achieved by overlaying precisely aligned 3D graphics derived from the patient's preoperative images onto the optical view of the microscope. Proof of principle and early phantom tests have been presented, for example, in Friets et al. [1989] and Edwards et al. [1995a,b].

4.3.1.1 Microscope (Optical System with Optical Axis); External Mount

A prototype AR system, called *MAGI* (microscope-assisted guided interventions), has been developed at Guy's Hospital, London, England. It provides 3D AR visualization for microscope-assisted interventions in neurosurgery and otolaryngology [Edwards et al. 1999, 2000; King et al. 2000]. *MAGI* is based on a Leica binocular operating microscope. Medical image information derived from MRI or CT scans of the patient's head or neck is inserted into the optical paths of both eyepieces via two monochrome VGA (640 × 480) displays and beam-splitters. Figure 4.4 shows the system in use and the augmented view through one of the microscope's oculars.

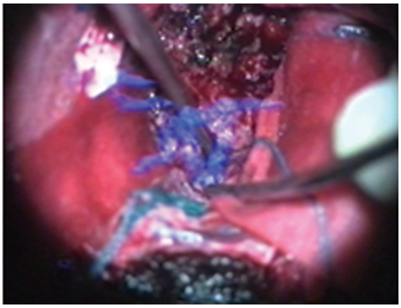


Fig. 4.4. *Left*: A device for microscope-assisted guided interventions (MAGI) developed at Guy's Hospital, London. *Right*: Augmented view through the microscope (pictures courtesy of Philip Edwards)

A set of infrared LEDs is attached to the microscope to mark its position, and then tracked by an optical tracking system (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada). For precise patient localization, the London group developed a locking, acrylic dental stent (LADS), which attaches to the patient's upper teeth, and contains LEDs for tracking with the Optotrak system. This LADS device replaces the standard surgical head clamp or bone implanted markers.

As has been shown in several clinical tests [Edwards et al. 1999], an operating microscope with AR image guidance can be used to perform difficult surgical interventions on both head and neck. For instance, the removal of a petrous apex cyst, where a more anterior approach was necessary to preserve hearing, was guided successfully using the MAGI device. The precision of the graphics overlay was reported to be better than 1 mm throughout the procedure.

4.3.1.2 Microscope (Optical System with Optical Axis); Head Mount

An approach similar to MAGI has been taken at the Allgemeines Krankenhaus Wien (AKH) Hospital in Vienna, Austria (intermittently the CARCAS Group at the University Hospital Basel, Switzerland), now using a head-mounted microscope instead of a free-standing, externally mounted microscope. The commercially available *Varioscope* is a head-mounted, lightweight operating binocular (Life Optics, Vienna) with autofocus, automatic parallax correction, and zoom. The group in Vienna has modified the *Varioscope* for stereoscopic AR visualization [Birkfellner et al. 2000a,b, 2002]. Clinical applications of operating binoculars, which typically have a 3x–7x magnification, include oral and cranio-maxillofacial surgery, plastic and reconstructive surgery, and also orthopedics.

Fig. 4.5. *Left*: The Varioscope AR, a head-mounted operating microscope with AR visualization, developed at the AKH, Vienna, Austria. *Right*: Augmented view through one of the oculars, for the scenario of endosteal implant insertion (left picture Birkfellner et al. 2002, © 2002 IEEE; Pictures courtesy of Wolfgang Birkfellner)

Figure 4.5 shows pictures of the prototype device, also referred to as the *Varioscope AR*, and the augmented view through one of the oculars. The original *Varioscope* contains prisms for image rectification to correct for image inversion in both optical paths. In the *Varioscope AR*, these prisms are modified on one side with a thin semitransparent coating and act as beam combiners. Two miniature LCD displays with VGA (640 × 480) resolution provide the computer-generated virtual images, and these images and the optical images of the real scene are focused into a common focal plane, avoiding focal disparity in the AR view (Fig. 4.6).

Calibration of the *Varioscope AR* has to take into account the variable zoom, and the variable convergence of the two individual optical paths [Birkfellner et al. 2001; Figl et al. 2005]. The *Varioscope AR* was designed to work with existing CAS systems. To study this AR device, it was integrated into a surgical navigation system for cranio- and maxillofacial surgery, also developed at AKH Vienna. The navigation system was based on optical tracking, and the same optical tracking was used to also keep track of the head-mounted *Varioscope AR's* pose.

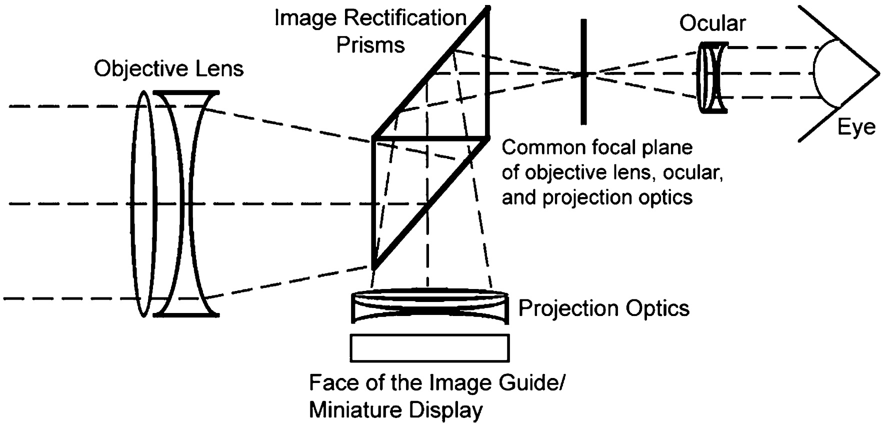


Fig. 4.6. The image rectification prisms of the Varioscope are used as beam combiners. Both the image from the real scene and the computer-generated image from the miniature display are focused into the same plane (picture Birkfellner et al. 2002, © 2002 IEEE; picture courtesy of Wolfgang Birkfellner)

4.3.2 Video AR Systems

Video-based AR systems capture the real view of a scene with video cameras and use a computer to augment it with virtual graphics. Head-mounted systems of this type are commonly called video see-through systems.

4.3.2.1 Video AR (Optical System with Optical Axis); Head Mount

AR for medicine was first proposed at the University of North Carolina (UNC), Chapel Hill, NC, USA, and its first implementation was in the form of a video see-through HMD system for ultrasound image guidance [Bajura et al. 1992; State et al. 1994]. The centerpiece of this system is a stereoscopic HMD, equipped with two miniature video cameras. The AR view is presented stereoscopically so the user has 3D perception based on stereo depth cues. Being able to change viewpoints, the user also experiences parallax depth cues, seeing objects in the foreground move faster than objects in the background. In this system, the HMD (and thereby the user's viewpoint) is tracked.

Early developments of the UNC system were targeted toward visualization of ultrasound images within a pregnant woman's womb (left image in Fig. 4.7). A 3D representation of the fetus could be seen in its actual location. Further research adapted this head-mounted video see-through approach for ultrasound-guided needle biopsies [Fuchs et al. 1996; Rosenthal et al. 2001, 2002; State et al. 2003, 1996].

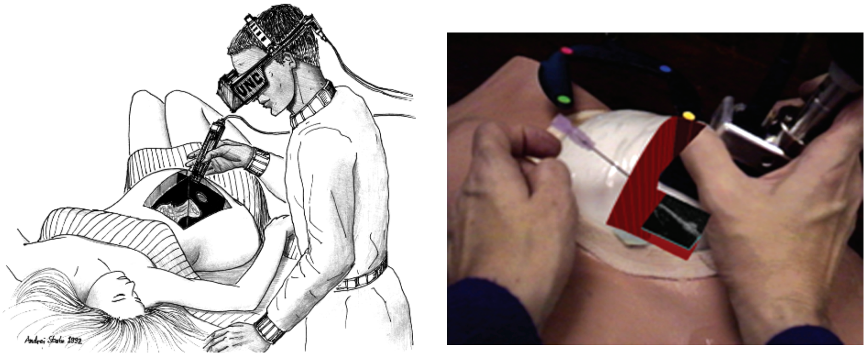


Fig. 4.7. UNC's approach for head-mounted video see-through augmented reality, which provides stereoscopic and parallax (kinesthetic) depth cues of the AR scene. *Left*: Schematic representation of AR fetus visualization. *Right*: AR view through the HMD during ultrasound-guided needle biopsies on breast phantom (right picture State et al. 1996, ©1996 ACM Inc., reprinted with permission; left artwork and right picture courtesy of Andrei State)

A version of UNC's AR system adapted for laparoscopic surgery is described in Fuchs et al. [1998]. As presented in Rosenthal et al. [2001], the UNC system uses optical tracking (FlashPoint 5000, Image Guided Technologies) of the HMD, ultrasound probe, and biopsy needle. The ultrasound image is visualized in its actual location within the patient. The AR view combines these ultrasound images with the video view of the patient, plus additional computer graphics, for example, a virtual object that identifies the location of a breast tumor (right image in Fig. 4.7). A randomized, controlled trial to compare standard ultrasound-guided needle biopsies to biopsies performed with UNC's AR prototype guidance system was used for evaluation of the system. Fifty biopsies of breast phantoms were performed by an interventional radiologist, and the method using AR visualization resulted in a significantly smaller mean deviation from the desired target compared with the standard ultrasound-guided method (1.62 mm for AR versus 2.48 mm for standard).

4.3.2.2 Video AR (Optical System with Optical Axis); Head Mount – Example 2

A stereoscopic video see-through AR system similar to the UNC system has been developed at Siemens Corporate Research in Princeton, NJ [Sauer et al. 2002c, 2000]. This system has been presented as the RAMP system, where RAMP stands for “Reality Augmentation for Medical Procedures.”

An ergonomic difference between RAMP and the UNC system consists in the downward tilt of the camera pair mounted on the RAMP HMD. This camera tilt allows the user to assume a more upright, relaxed position when looking down at the workspace. Another difference lies in the tracking systems. Whereas the UNC system initially used the color cameras for tracking, which provided the real view of the scene, it was later equipped with a commercial tracking system for “outside-in” tracking. In contrast, the RAMP system was developed with a third camera on the HMD dedicated to inside-out tracking. This tracking camera is a black-and-white camera with a wide angle lens and is equipped with an infrared LED flash, placed as a ring around the lens. The tracking camera works in conjunction with retro-reflective optical markers that are framing a surgical workspace. Using this head-mounted tracker camera, the user cannot accidentally step in the way of the tracking system, making the typical line-of-sight restriction of optical tracking systems less limiting. Having the camera on the head also optimizes the perceived accuracy of the augmentation. Movements along the optical axis are tracked with a lower accuracy than transverse movements, but at the same time, a depth error of a virtual object’s position is also less perceptible than a lateral error. In other words, when scene and tracker camera look in the same direction, the camera detects just what the user can see. What the camera cannot detect, the user cannot see either. The head-mounted tracking system was extended later beyond head-tracking to include also instrument tracking [Vogt et al. 2002]. As in the UNC system, the user’s spatial perception is based on stereoscopic depth cues, and on parallax depth cues from viewpoint variations.

The three cameras are genlocked to each other, with the benefit that tracking information is available exactly for each frame that needs to be combined with computer graphics. This synchronization eliminates any time lag between the real and virtual components of the AR view. The Registration accuracy of the augmentation measured in object space is around 1 mm. The augmented images also appear stable, with no apparent jitter. Overall, there is a time latency of about 0.1 s between an actual event and its display. The RAMP system runs in real time at 30 frames per second and displays an augmented stereoscopic video view with XGA resolution for each eye. A new system design replaced the three networked SGI workstations of of the initial RAMP system with a single PC and improved the overall performance [Vogt et al. 2006, 2003].

Figure 4.8 shows the RAMP HMD and an augmented view in preparation of a neurosurgical procedure. The system has been put into a neurosurgical context [Maurer et al. 2001; Wendt et al. 2003], adapted to an interventional MRI operating room [Sauer et al. 2001a, 2002b], tested for CT- and MRI-guided needle placements on phantoms [Das et al. 2006; Khamene et al. 2003b; Sauer et al. 2002c, 2003] and pigs [Vogt et al. 2004b; Wacker et al. 2006], integrated with an ultrasound scanner [Khamene et al. 2003a; Sauer et al. 2001b, 2002a], and transformed into a 3D medical data exploration tool [Vogt et al. 2004a].

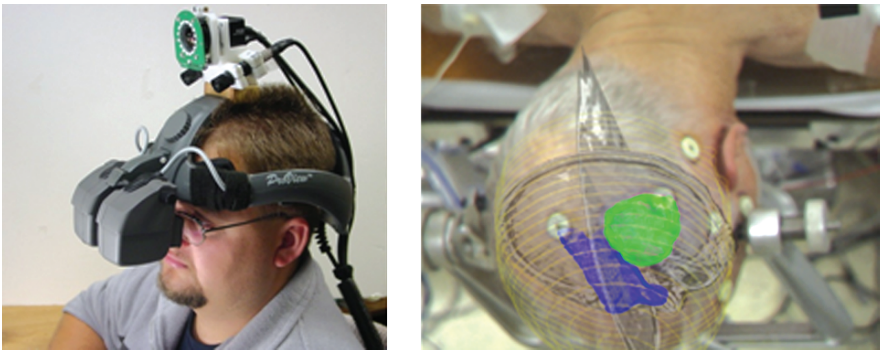


Fig. 4.8. RAMP system developed by Siemens Corporate Research Inc. *Left*: Stereoscopic video see-through HMD for interventional AR visualization with a dedicated third camera for tracking. *Right*: Augmented view of patient's head before neurosurgery (left figure is from Khamene et al. 2003b, with kind permission from Springer Science and Business Media)

At the Technische Universität of Munich, the RAMP system has been adapted to new applications [Heining et al. 2006; Sielhorst et al. 2004a,b], such as a birth simulator, where AR visualization may increase the efficiency of the training and provide support during a difficult procedure such as a forceps delivery.

4.3.3 Large Screens

A category of AR system uses large, stationary screens for display of the AR view. Opaque displays are used for video AR systems and semitransparent screens are required for optical AR systems.

4.3.3.1 Large-Screen Video AR (Optical System with Optical Axis); External Mount, Monoscopic

A large-screen video AR system was developed at the MIT AI Lab for the purpose of image-guided neurosurgery, and studied in close collaboration with the Surgical Planning Laboratory at Brigham & Women's Hospital, Boston, MA [Grimson et al. 1995, 1998, 1999].

In this system, a video camera placed close to the surgical scene provides the live video images of the patient. The patient's head, as well as the surgical instruments, are tracked by an optical tracking system (Flashpoint, Image Guided Technologies Inc.), for which LEDs are attached to the neurosurgical head clamp and the surgical instruments. To register the medical information from the MRI scan to the actual patient position in the head clamp, 3D surface points of the patient's scalp are collected with a laser scanner or a tracked pointer. The collected points are registered with the skin surface, which is extracted from the patient's MRI scan [Grimson et al. 1994, 1996]. During the interventional procedure, these registration parameters are used to align medical images from the MRI scan with the video image of the patient's head. The augmented video image on the monitor screen displays the patient in a transparent fashion, with internal anatomical structures from the MRI dataset overlaid on the video of the head. A tracked pointer is also visualized in this augmented view. Besides the augmented view, the system can display three orthogonal MRI slices in separate windows, selected with the tracked pointer as in traditional navigation systems. Figure 4.9 shows a neurosurgical intervention with the AR monitor screen above the surgical site and an example image of an argumented view of the patient. The AR system is set up in an interventional GE SP/i MR scanner (General Electric Medical Systems, WI).

Grimson and his colleagues [1998] at Brigham and Women's Hospital report that this AR image guidance system for neurosurgery has been used on 70 patients. It effectively supported the surgery in planning the craniotomy, identifying margins of tumor, and localizing key blood vessels. A wide range of neurosurgical cases were selected to evaluate the efficiency of the system, including tumor resection, pediatric epilepsy, meningioma, and biopsy cases. Limitations of the system are its fixed viewpoint, which does not coincide with the surgeon's direct viewpoint, and its monoscopic function, which does not provide 3D perception.

Fig. 4.9. Monitor-based video AR system for image-guided neurosurgery. Patient's head augmented with internal structures, which were extracted from an MRI scan (picture Grimson et al. 1996, © 1996 IEEE; Picture courtesy of W. Eric L. Grimson)

4.3.3.2 Large-Screen Optical AR (No Optical Axis); External Mount, Monoscopic/Stereoscopic

At the Carnegie Mellon University (CMU) Robotics Institute, Pittsburgh, PA, the MRCAS group (Medical Robotics and Computer Assisted Surgery) developed an image overlay system based on a semitransparent mirror placed above the surgical workplace [Blackwell et al. 1998a,b, 2000]. A high-resolution flat LCD panel is mounted above the half-silvered mirror, which acts as a beam combiner. The physician looks through this screen at the patient and simultaneously sees the reflection of the LCD display. This configuration creates the illusion of perceiving the virtual image below the screen inside the surgical workplace. Display and mirror are jointly attached to an articulated arm. An optical tracking system (OptoTrak, Northern Digital, Waterloo, Ontario, Canada) tracks patient, display/monitor setup, and the user by means of attached LEDs. Figure 4.10 illustrates the concept and its realization as a prototype system.

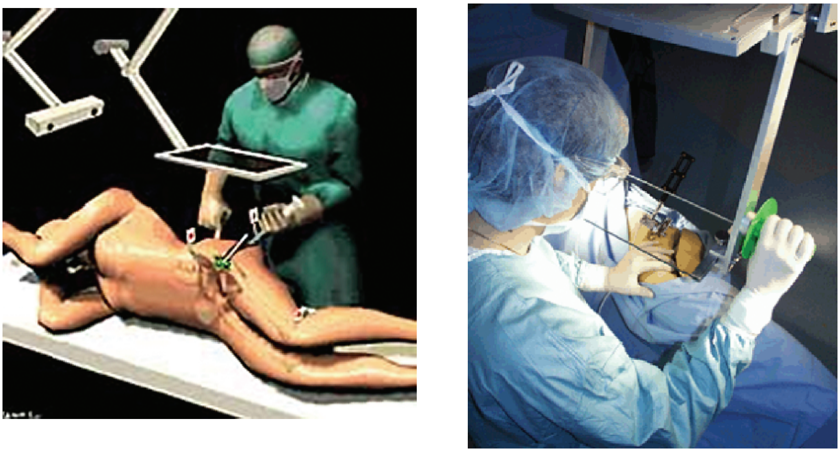


Fig. 4.10. Large-screen image overlay system for interventional image guidance or surgical education, developed at CMU's Robotics Institute. *Left*: Illustration of the concept. *Right*: Prototype system in use (pictures courtesy of the Carnegie Mellon Robotics Institute)

Potential applications include orthopedic surgery, neurosurgical procedures, and surgical education [Blackwell et al. 1998b]. Blackwell et al. [1995] describe an earlier prototype system from CMU based on a CRT monitor, which provided proof of concept of the monitor/mirror approach. It was the CRT monitor that made stereoscopic visualization possible. To create 3D perception, shutter glasses were used, with the monitor rendering a different view for each eye synchronized to the shutter glasses. In this way, the system provided stereoscopic depth cues for the virtual scene. As the real scene was observed directly through the semitransparent mirror, it appeared naturally in three dimension anyway.

4.3.3.3 Large-Screen Optical AR (No Optical Axis); External Mount, Stereoscopic – Example 2

Figure 4.11 shows another AR system that follows the transparent screen approach [Goebbels et al. 2003].

The *ARSyS-Tricorder* has been developed in Germany by multiple institutions in collaboration with the Fraunhofer-Gesellschaft, and utilizes a setup with a stereoscopic projector instead of a monitor to display the virtual graphics. The graphics appear on a polarization preserving projection screen, and are reflected to the eyes of the user by a half-transparent mirror.

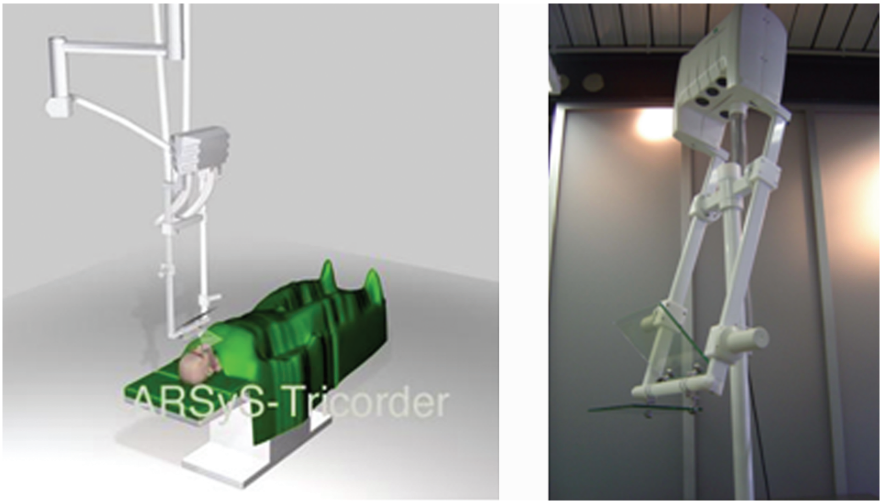


Fig. 4.11. ARSyS-Tricorder – AR system with projection system and semi-transparent mirror. *Left*: Illustration of the concept. *Right*: ARSyS-Tricorder prototype system (pictures © Fraunhofer Institut Intelligente Analyse- und Informations-syteme (IAIS), Sankt Augustin, Germany)

The user wears polarized glasses, which allow him to perceive the virtual images in stereo through the mirror. User, patient, and the combination of projector, projection screen, and mirror must be tracked for proper registration between the real view of the patient and the overlaid virtual medical graphics.

4.3.3.4 Large-Screen Video AR (Optical System with Optical Axis); External Mount, Monoscopic – More Examples

Lorensen et al. [1993, 1994] described an early prototype of a monitor-based video AR system for neurosurgical procedures. There still is current interest in the concept of a single stationary monitor displaying an augmented video view of the patient.

Hayashibe et al. [2005] describe a prototype system, which has been developed at Jikei University School of Medicine in Tokyo, Japan. Intra-operatively acquired volumetric images from a mobile C-arm x-ray system are used to overlay the patient's internal anatomy onto the camera view of the patient in the operating room (left image of Fig. 4.12).

Fig. 4.12. *Left*: An AR system that combines a video view of the patient with intraoperatively acquired scans of a mobile X-ray C-arm, developed at Jikei University School of Medicine, Tokyo, Japan. *Right*: Augmented reality guidance for liver punctures with a prototype of a screen-based video AR system developed at IRCAD University Hospital, Strasbourg, France (left picture from Hayashibe et al. 2005 and right picture from Nicolau et al. 2005a, with kind permission of Springer Science and Business Media)

A screen-based video AR system to guide liver punctures for radiofrequency tumor treatment is being developed at IRCAD University Hospital, Strasbourg, France, in collaboration with INRIA Sophia-Antipolis, France [Nicolau et al. 2005a]. As the right side of Figure 4.12 shows, a larger number of skin markers are used for patient to image registration. In a stationary abdominal phantom, the system achieves a target precision of 3 mm. The first *in vivo* experiments have been presented in Nicolau et al. [2005b]. The common problem of respiratory motion for interventional guidance of abdominal procedures remains, and currently restricts the application of this system to larger targets with a diameter above 3 cm.

A unique AR video system has been reported in Mitschke et al. [2000] and Navab et al. [1999]. The CAMC system, short for Computer Augmented Mobile C-arm, attaches a video camera next to the x-ray source in a mobile C-arm, and by means of two mirrors aligns viewpoint and optical axis of the video camera to those of the x-ray system (Fig. 4.13). The result is a “dual energy imaging system”; both x-ray and video camera images of the patient are taken from the same viewpoint, but with different energy spectra. The video image shows the surface of the patient’s body and objects located in front of it, while the x-ray image shows the inside of the body. The whole system is calibrated so that x-ray and video images can be overlaid in a registered way.

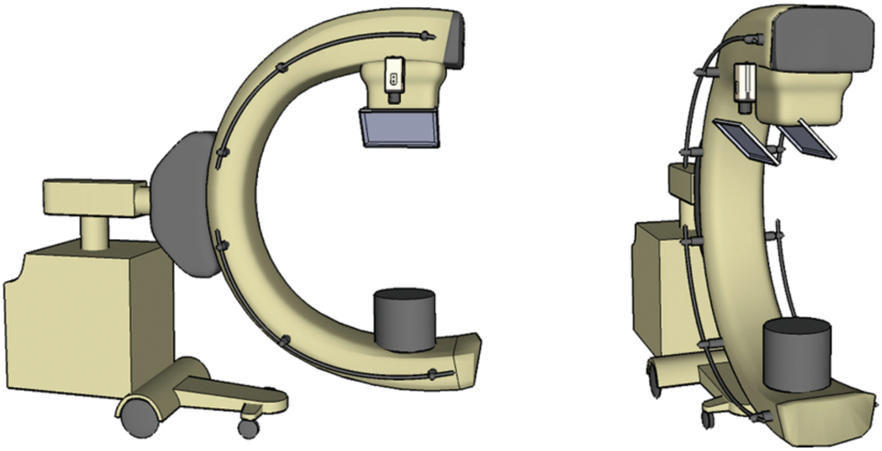


Fig. 4.13. Schematic drawing of CAMC. A mobile C-arm is equipped with a video camera and a double mirror system, aligning the video view with the X-ray view (pictures courtesy of Joerg Traub)

One application for CAMC is to guide needle placement during biopsies, as the x-ray image helps to identify an internal target. The initial alignment of the needle (outside of the patient) can then be performed under AR guidance without the need for additional x-ray radiation. The video image shows the external needle, which needs to be aimed at the target, and the overlaid x-ray image shows the location of the internal target.

4.3.4 Tomographic Overlays

Tomographic overlays are a special case of screen-based optical AR systems. Again, the user looks through a semitransparent mirror and sees the reflection of a monitor overlaid onto the view of the real scene. The feature of tomographic overlays is that, independent of the user's viewpoint, the mirror image of the monitor appears in a fixed position within the real scene. The physical monitor is just an object in the real environment, and the location of its mirror image depends only on the position of the mirror, not on the viewer. While the planar image on the monitor limits the AR view to the overlay of flat 2D virtual images, proper positioning of monitor and mirror and appropriate system calibration ensure that the 2D virtual image appears in the correct position with the appropriate scale within the 3D AR scene. This simple concept enables the augmented scene to be properly appreciated by multiple untracked observers, without the requirement of special eyewear.

4.3.4.1 Optical AR with Screen (No Optical Axis), 2D Virtual Images Only

The use of tomographic overlays for ultrasound imaging has been proposed and is being developed at the Visualization and Image Analysis (VIA) Laboratory at the University of Pittsburgh and Carnegie Mellon University [Stetten et al. 2000, 2001; Stetten and Chib 2001b]. Real-time ultrasound images appear in the actual position of the patient's anatomy, and the term *Real Time Tomographic Reflection (RTTR)* has been introduced for this approach.

Figure 4.14 shows a prototype of the VIA Lab's *sonic flashlight*. A flat-panel display attached to a B-mode ultrasound probe displays the live ultrasound image. This image is reflected in a half-silvered mirror, attached to the probe in a way that the displayed image of the ultrasound scan appears at the actual scan location. It provides the AR view with the correctly positioned 2D ultrasound image without the need of a tracking device. Figure 4.15 illustrates this principle.

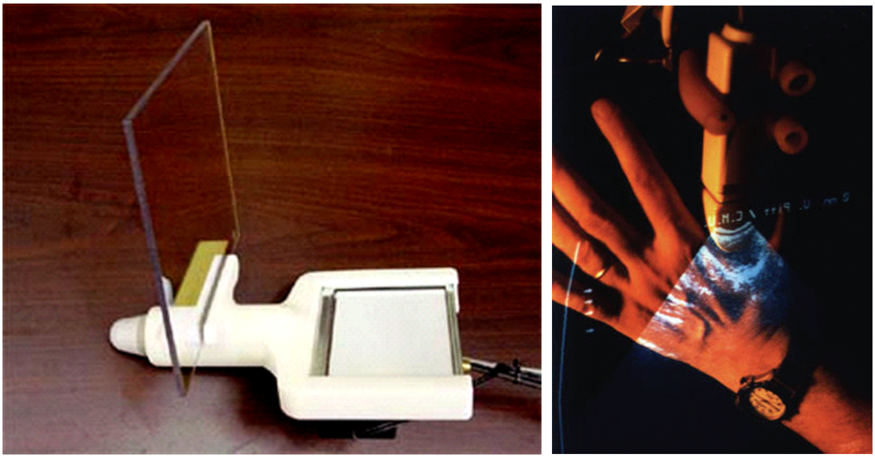


Fig. 4.14. A prototype of the *sonic flashlight*, developed at VIA Lab, Pittsburgh, PA. *Left*: A small flat-panel monitor is attached to the handle of an ultrasound probe. A half-silvered mirror bisects the angle between ultrasound plane and display. *Right*: Example of a tomographic overlay with the sonic flashlight (pictures courtesy of George Stetten)

Subsequent research has adapted this concept to develop magnified real-time reflection of ultrasound for remote procedures [Stetten and Chib 2001a], a C-mode sonic flashlight for a matrix array ultrasound probe [Stetten

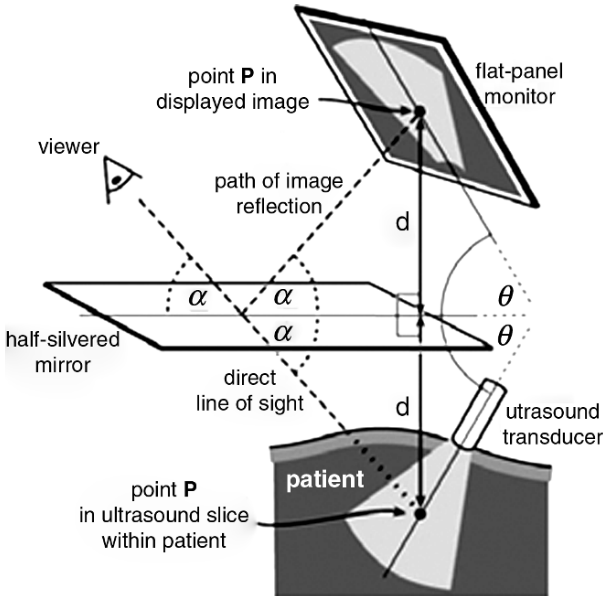


Fig. 4.15. The principle of real-time tomographic overlay as implemented in the sonic flashlight. Due to the geometric relation among half-silvered mirror, flat-panel display, and ultrasound transducer, each point in the virtual ultrasound image is precisely located at its corresponding physical 3D location (picture courtesy of George Stetten)

et al. 2003, 2005], and integrated the sonic flashlight with a laser guide for needle procedures [Wang et al. 2005]. Chang et al. [2005a] describe how the sonic flashlight was used for a cadaver study in a neurosurgical context, where the users localized a brain lesion with a needle, supported by ultrasound guidance. Compared to conventional ultrasound guidance, where the ultrasound image appears on a separate screen apart from the ultrasound probe and the patient, they reported that the sonic flashlight improved hand–eye coordination and helped to place the needle easily and intuitively into the lesion. Chang et al. [2005b, 2006] report on the successful use of the sonic flashlight for catheter placement.

4.3.4.2 Optical AR with Screen (No Optical Axis), 2D Virtual Images Only; External Mount – Example 2

The tomographic overlay concept, where no tracking is needed and which has been realized for ultrasound in the form of the sonic flashlight, can be adapted to other imaging modalities. At the CISST Lab at Johns Hopkins University, in collaboration with Tokyo Denki University, a prototype system has been developed to support percutaneous therapy performed inside a CT scanner [Fichtinger et al. 2005a,b, 2004; Masamune et al. 2002].

The overlay system comprises a flat-panel LCD display and a half-silvered mirror, attached to the gantry of a CT scanner.

Figure 4.16 shows the system on the left side. This prototype system has been evaluated for needle placements in phantoms and cadavers, guided by the tomographic overlay of CT slices in the scanner. Skeletal targets could be reached with one insertion attempt, and liver targets could be assessed successfully, although tissue deformations posed some challenges. By providing accurate and intuitive image guidance, the system can improve the learning curve for physicians in training, and help reduce the procedure time and x-ray dose for CT-guided needle procedures.

The right side of Fig. 4.16 shows a similar approach to AR from the same group at the CISST Lab at Johns Hopkins University, to guide needle placement procedures on a closed bore MRI scanner [Fischer et al. 2006, 2007]. A target application is MR arthrography (MRAr), where a needle is driven under fluoroscopy or CT guidance into a joint, and a diagnostic assessment is made based on MRI images of the contrast-injected joint. Preclinical trials of the proposed AR-guided procedure on the MRI scanner bed resulted in repeatedly successful first-attempt needle placements into the joint of porcine and human cadavers and show the system's potential to effectively support and simplify the overall arthrography procedure by eliminating radiographic guidance during contrast injection.

Fig. 4.16. Tomographic overlay systems for percutaneous therapy inside a CT or MRI scanner developed at CISST Lab at Johns Hopkins University. *Left*: The prototype system with monitor and half-silvered mirror attached to the CT gantry during a cadaver needle placement experiment. All observers see the 2D cross-sectional CT image in the same correct position. A marker is attached to the needle, indicating the length of the needle that has to be inserted to reach the target at the correct depth. Otherwise, the needle is not being tracked, and its actual position inside the patient can only be assessed with a CT control scan. *Right*: The overlay system constructed around an MRI scanner bed guiding a needle placement procedure (pictures courtesy of Gabor Fichtinger and Gregory Fischer)

4.3.4.3 Optical AR with Screen (No Optical Axis), Tomographic Overlay for 3D

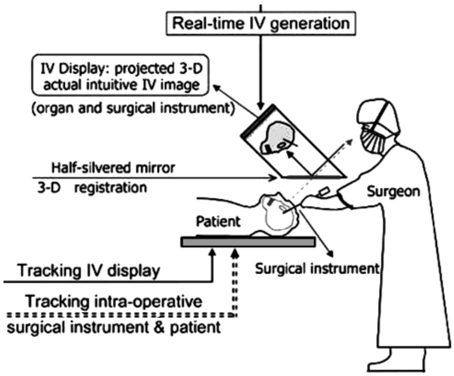
The concept of the tomographic overlay is limited to the overlay of 2D images because of practical reasons. We display a 2D image as a light distribution on a 2D monitor, and perceive it consistently at the monitor's position in space. If we had true 3D monitors giving a consistent image of a 3D object independent of our viewpoint, we could as well employ a semi-transparent mirror and perceive the reflection of this 3D virtual object as part of the 3D real scene. Unfortunately, a stereo display does not produce a true 3D image. When the user moves the head to the side, the 3D image moves along and does not stay in a fixed position in space as would a real object.

Masamune et al. [2000] present a mirror-based AR system where the 3D display is implemented as a flat 2D display screen scanning through a volume, building up the 3D image slice by slice. Accordingly, the display system is called the "slice-display." A similar 3D display with a rotating screen is commercially available from the company Actuality Systems (Bedford, MA). Currently, such a 3D display system is still expensive and has limited resolution and contrast.

An earlier approach to augment a neurosurgical site with 3D images was based on integral photography [Iseki et al. 1997; Masutani et al. 1995, 1996]. Integral photography is a 3D imaging method that uses a lenslet array to record and display an object from a range of viewpoints within a given viewing angle. Integral photography images of three-dimensional medical data were recorded on film, which took several hours. During surgery, those integral photographs were superimposed on the patient with a half-silvered mirror. Since this *Volumegraph* does not involve computer screens, but uses conventional film, the image could not be altered during the surgery.

At the University of Tokyo, researchers introduced integral videography (IV) for medical AR, replacing the film in the Volumegraph with one or more high-resolution LCD displays [Liao et al. 2001, 2004, 2006; Nakajima et al. 2000]. Figure 4.17 illustrates the principle and shows a prototype system.

An optical tracking system (Polaris, Northern Digital Inc.) keeps track of the positions of surgical instruments and patient. Both models of the surgical instruments and the 3D patient data are overlaid as IV images during the surgery. The first phantom experiments showed that needle placement procedures could be guided with this system, with a mean error below 3 mm [Liao et al. 2004]. The pixel density of the display and the lens pitch are the main factors for the quality of the IV image. The virtual scene has to be rendered and displayed simultaneously for all the different viewpoints within the viewing range. This not only requires a very high display resolution to spatially multiplex all the different views, but also a correspondingly high processing power to render all the images. Approaches to build higher-resolution IV displays are being investigated and described in Liao et al. [2002].



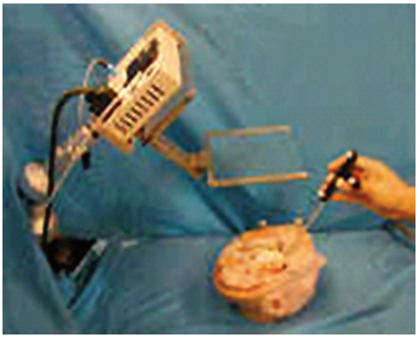


Fig. 4.17. Surgical navigation by integral videography image overlay, developed at the University of Tokyo. *Left*: Illustration of the concept, where the surgeon perceives 3D image overlay without the need for stereo glasses. *Right*: Prototype system (picture Liao et al. 2004, © 2002 IEEE)

4.3.5 Video Endoscope Systems

Endoscopes and laparoscopes are viewing instruments for minimally invasive surgery. They are equipped with video cameras and acquire "real" images from within cavities in the patient. These video views can also be augmented with corresponding medical images. Although the video view can only show outer surfaces, the medical images add information on anatomical structures that lie behind the surfaces.

The system described in Shahidi et al. [1998], developed at the Image Guidance Laboratory at Stanford University (Palo Alto, CA), tracks an endoscope with an optical tracking system and presents a side-by-side display of the endoscopic video view and a corresponding virtual endoscopic view, generated by volume rendering of preoperatively acquired CT or MR data. The virtual endoscope can make opaque tissue transparent and give the surgeon a look beyond the visible surface captured by the real endoscope. Both images, from surgical and virtual endoscopes, can be blended together to show an AR view on the monitor.

A similar approach has been described in De Buck et al. [2001] for laparoscopic procedures. A laparoscope is a rigid endoscope for procedures in the abdomen. The prototype system overlays the video images from the laparoscope with virtual graphics extracted from preoperative CT scans. An optical tracking system keeps track of the laparoscope's position with respect to the patient. One potential application is the visualization of the ureter as a virtual object in the laparoscopic view of the pelvis. Locating the ureter is a common challenge in laparoscopic surgery.

The augmented visualization of endoscopic images during robot-assisted coronary artery bypass graft (CABG) surgery is described in Coste-Maniere et al. [2004] and Mourgues et al. [2001, 2003]. The ChIR Medical Robotics Group at INRIA developed the system on the *da Vinci* platform (Intuitive Surgical Inc., Sunnyvale, CA) and tested it in animal trials. Figure 4.18 shows the setup and an AR visualization of the coronary tree. A model of the coronary tree, extracted from preoperative angiograms and CT data, is overlaid on the endoscopic images for extra guidance during the minimally invasive procedure. Registration of the real images and computer models poses a particular challenge for the beating heart. An initial registration is based on skin markers, and an interactive method during the procedure allows the surgeon to correct the overlay in real time. The system's evaluation on a dog and a sheep model showed its effectiveness in helping the surgeon localize target structures during the robot-assisted CABG procedure. In addition, Traub et al. [2004] report on the use of AR visualization in robot-assisted minimally invasive cardiovascular surgery.

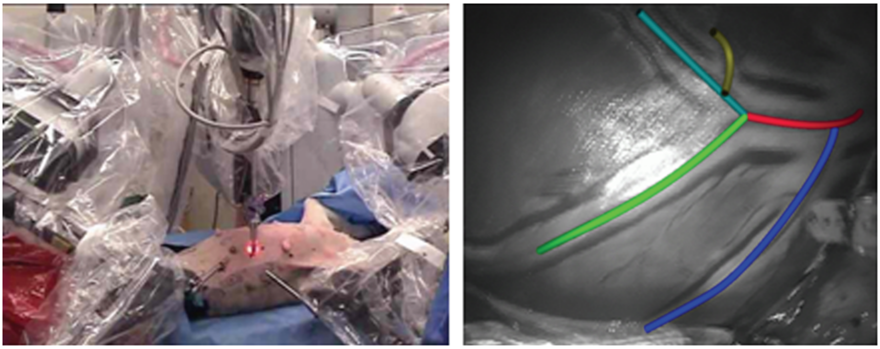


Fig. 4.18. Method for augmentation of endoscopic images during robot-assisted coronary artery bypass graft surgery with the *da Vinci* system, developed at INRIA. *Left*: Setup of the da Vinci system for an animal study of the proposed method. *Right*: Overlay of the coronary tree model on an endoscopic image of the da Vinci system (pictures reproduced with permission from Coste-Maniere et al. 2004, © 2004, by permission of SAGE Publications Ltd)

Endoscopy plays an important role in the further development of minimally invasive techniques. The combination with 3D medical imaging can not only extend the endoscopic view beyond the surface, but can also provide a global context for the local endoscopic views. AR visualization is just one possibility for displaying the combined information. Dey et al. [2000] describe a method of extracting surface shapes from preoperative images and mapping endoscopic images onto these 3D shapes.

4.3.6 Other Methods: Direct Projection

Graphical information can be directly projected onto the patient, also augmenting the physician's view. For practical reasons, the direct projection approach is limited to simple 2D graphics that appear on the skin surface: points, lines, and outlines. The patient is usually draped around the surgical site and does not provide a good projection screen. As a projected image moves and gets distorted when location and shape of the screen change, precise measurement of location and shape of the skin surface is necessary to make the guiding graphics appear correctly registered to the patient.

Glossop et al. [2003] describe a system with infrared and visible lasers. The infrared lasers assist with the registration, and the visible lasers project graphics guides onto the patient's skin, such as an entry point or a surgical plan [Marmurek et al. 2006].

A similar approach has been described by Hoppe et al. [2002, 2003] and Worn and Hoppe [2001]. Here a video projector projects the surgical plan onto the patient. For registration, the surface shape is measured using structured light and two video cameras that evaluate the projected patterns on the patient.

4.4 System Features Overview

The different types of systems have unique characteristics. In this section, we are listing the important features of the standard systems in bullet point format for a comparative overview.

4.4.1 Microscope Systems

1. They exhibit excellent quality of the optical images. To preserve the brightness of the optical image, one usually uses an interferometric beam combiner to inject the virtual image into the optical path. This limits the electronic display to be monochromatic.
2. By injecting the graphics into an intermediate focal plane of the optical system, focal disparity can be avoided – the user can see real image and virtual graphics in the same focal plane.
3. The system can be equipped with a beamsplitter to acquire video images of the AR view so that the camera sees the same image as the user. The resulting hybrid system shares important characteristics of a video AR system. The AR view can be displayed live for additional observers, or can be recorded for documentation. Furthermore, system calibration (see Section 4.4.5) can be performed in a user-independent way by processing the video images in the computer.

4. If a microscope is already a standard tool for a procedure, AR can be introduced in a very evolutionary and unobtrusive way. Physicians can continue to work as usual, and can consult AR visualization optionally without the need for extra equipment.

4.4.2 Video AR HMD Systems

1. Video AR systems can be readily equipped with good displays. This leads to very good quality virtual images (whereas the quality of the real images may be compromised by the intermediate video process).
2. Real and virtual images are blended electronically, which allows an optimal control of the resulting AR view. For example, one can reduce disturbing highlights in the real image, or adapt the brightness and contrast of the virtual image to the brightness of the real image for improved visibility.
3. The AR view is available in electronic form and can be stored for documentation. It can also be shared in real time with a larger audience.
4. As the AR view is available in electronic format, registration between real and virtual images can be calibrated in an "objective" (user-independent) manner. In addition, the registration accuracy can be monitored online.

4.4.3 Semitransparent Screens

1. Calibration is subjective as only the user can see the AR view, resulting in a user-dependent calibration procedure of limited accuracy.
2. For correct perception of the virtual scene, the user must assume a well-defined eye position with respect to both the display screen and the patient anatomy. This makes tracking more challenging compared to the systems discussed above and below, since the introduction of three independent coordinate systems, namely the user (viewpoint), the patient, and the screen, introduces more errors.

   In contrast, for microscope-based systems, the user does not have the freedom to assume an arbitrary viewpoint, as a well-defined eye-position is given by the exit pupil of the microscope – so the user does not have to be tracked. For video-based AR systems, the location of the electronic display does not influence the registration and need not be tracked. The position of the user's eyes relative to the display does not matter either; only the cameras need to be tracked, as they provide the real images in relation to the patient.
3. Stereo visualization is required not only to perceive the virtual graphics at the appropriate depth, but also to provide correct alignment of the

virtual features to the real scene. A practical implementation of stereo imaging requires that the user to wear glasses that separate the left and right eye images, for example, shutter glasses to separate temporally multiplexed stereo images.
4. Screen and patient are not in the same plane. The user needs to focus on virtual and real images separately, which diminishes the AR experience.
5. Sterility of the semitransparent screen is an issue that needs to be considered for practical surgical applications.

4.4.4 Tomographic Displays

1. Tomographic displays provide AR visualization without the need to track the user, who can still move and change viewpoints. This makes this concept simple and robust.
2. In practice, virtual images are limited to two dimensions. With a true 3D display – not just stereo – 3D imaging would be possible. But there are, at least currently, no practical solutions for a suitable 3D display.

4.4.5 Optical See-Through HMD Systems

1. Optical see-through HMD systems without an optical axis have not been discussed in this chapter, as they are basically unsuitable for medical AR applications (which require precise registration between real and virtual images according to our understanding of medical AR). However, the comparison of optical versus video see-through systems has been a topic of discussion, so we list some of the arguments here.
2. Calibration of the registration can only be performed by the user, subjectively aligning virtual and real structures. The accuracy of such a subjective calibration method is limited.
3. The registration between the real and the virtual images depends critically on the position of the user's eyes behind the small screen. Movement of the head-mounted display on the user's head can result in large registration errors, which can go unnoticed by the user and are not detectable by external means. This is a big safety concern in the context of medical image guidance.
4. Furthermore, as a head-mounted display cannot be put onto the user's head in a precisely reproducible position, the calibration process has to be repeated each time it is put on.

4.5 Technical Challenges and Fundamental Comparisons

For practical applications, there should be three basic requirements to perform meaningful comparisons: right place, right time, and right way.

4.5.1 Right Place: Calibration

Medical AR requires that the real images and the virtual images are spatially well registered. For this, the AR system needs to be calibrated before use, and objective calibration is necessary to achieve precise, user-independent results. For objective calibration, video images of a real scene are acquired and brought into correspondence with a corresponding virtual model. This is straightforward with video AR systems, as video images are readily available. Sauer et al. [2000] and Vogt et al. [2006] describe this calibration process in more detail. For optical AR systems that have an optical system with optical axis, a camera can be inserted instead of the user's eye, and objective calibration can be performed. A major drawback of the screen-based systems, where the user's eye position is variable, is that only the users can calibrate the system for their own use. This subjective calibration [Tuceryan and Navab 2000] provides results that are less precise than that in the case of objective, completely computer-based user independent calibration.

4.5.2 Right Time: Synchronization

We also need the correct registration to persist when movement is present. When the user moves and changes his viewpoint or moves an instrument, the image update in the real view and the virtual view should be synchronized. At any given time, the objects in the real view and in the virtual view should be correctly aligned.

It is in the nature of optical AR systems that the real view appears instantaneously. The information in the virtual view, however, is necessarily delayed because of the finite speed of tracking and rendering. This results in an unavoidable time lag between real and virtual images.

Video AR systems exhibit a delay for both real and virtual images. The real images are recorded by a video camera, transferred to the computer, and rendered in combination with the virtual images. This process takes the time of about 2–3 video frames or 60–90 ms. With proper synchronization of video acquisition and tracking, one can eliminate any time lag between real and virtual images and create a consistently correct AR view, but of course, at the price of an unavoidable overall delay [Sauer et al. 2000].

4.5.3 Right Way: Visualization and Perception

We need to show accurate information in the AR view, and we need to visualize it in the right way to achieve optimal perception. Even if real and virtual images are combined in correct alignment, the user does not necessarily *perceive* their correct spatial relationship.

The virtual view cannot provide all the depth cues that we experience in the real world. If a direct optical view is substituted with a video view, in place of the real view, we lose further depth cues. With the video view, we are limited to stereoscopic depth cues (if we have a stereoscopic AR system), parallax cues (if we wear a head-mounted display or can vary our viewpoint behind a large screen), and sharpness cues. The sharpness depth cue leads already to a perception mismatch between the real and virtual views. The real view has always a limited depth of focus; real objects too close to the user, or too far away are out of focus and appear blurred. In contrast, a practical rendering of the virtual view is sharp throughout and does not include a depth-dependent defocusing. This mismatch contributes to the difficulty of perceiving the correct spatial relationship between real and virtual views.

More important in this respect, however, is the issue of occlusion. When real and virtual objects are overlapping in a way that does not reflect their correct spatial relationship, depth perception becomes more difficult. We know the viewer's viewpoint and can make the graphics objects appear at the desired 3D locations. However, correct interaction between real and graphics objects would require 3D information about the real objects as well. Is a real object in the scene in front of or behind the location of an overlapping virtual object? This 3D information is usually not available; the graphics objects are simply superimposed onto the 2D images of the real scene. In this way, real objects can be hidden by virtual objects, but not vice versa. However, closer objects are not supposed to occlude objects that are farther away, which is the well-known occlusion problem in AR. Wrong occlusion triggers conflicting depth cues: if stereo depth cues suggest that a virtual object is farther away than a real object, but at the same time the virtual object occludes the real object, the brain's depth perception is confused. The brain may still accept a transparent patient (Fig. 4.19), but will not process the transparent physician scenario properly.

For correct occlusion, one needs to obtain 3D information of the real scene. Sauer et al. [2001a] report, however, that one can reduce the disturbing effect of wrong occlusion cues significantly with appropriate rendering of the graphics; showing segmented structures not as solids

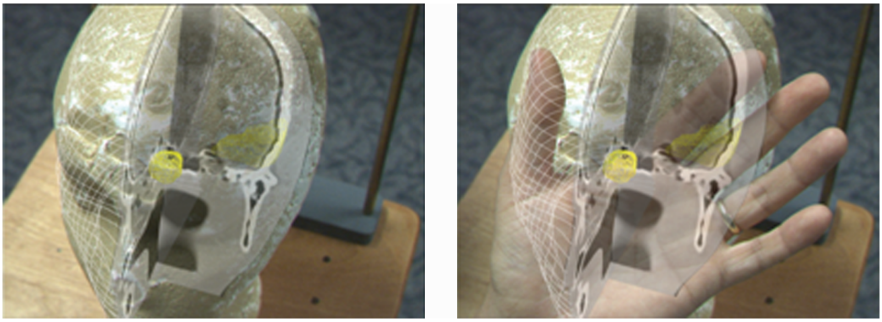


Fig. 4.19. AR view of head phantom. *Left*: Transparent patient. *Right*: Transparent physician (left figure is from Vogt et al. 2002, © 2001 IEEE)

but as wire frames; not with thick lines but with thin lines; not opaque but semi-transparent. The overall guideline is to show only the relevant structures in a sparse representation, avoiding occlusion as much as possible. This approach is very much in line with regarding the virtual images as maps, as relevant information abstracted from the original medical images that contain irrelevant details.

Another approach is to avoid the occlusion problem altogether by making all the relevant information available in the virtual images. This requires tracking of the surgical instruments in the same way as for standard navigation systems. Sauer et al. [2002b] describe an experiment in which a neurosurgeon used an elongated surgical tool called a rongeur, the position of which was not tracked, to extract hidden targets from a phantom. As long as the targets were only 2–3 cm below the surface, the neurosurgeon was successful in locating them with his rongeur, based on an AR view with a real view of the instrument only. For very deep-lying targets, however, the AR view did not sufficiently support the minimally invasive approach. The main reason, of course, was that the surgeon lost sight of the instrument tip once it was inserted into the phantom, and could not accurately extrapolate its location from the external part of the instrument. He could see the location of the target, but not the location of the instrument. The same paper describes another experiment, where a tracked needle was used to locate deep-lying targets in a similar phantom. The AR view now included a virtual model of the instrument, and the task became very easy as the surgeon could consistently and accurately see the spatial relationship of instrument and target throughout the procedure.

Not only is instrument tracking necessary to visualize a hidden instrument, it also helps to get around the AR occlusion problem. As both target and instrument locations are known in three dimension, they can be visualized and perceived with correct occlusion in the virtual scene. The real part of the AR view becomes less important and mainly serves to keep the surgeon connected to the patient and observe complications. This visualization moves more toward an augmented virtuality scenario, where the virtual scene essentially contains all the important information. Video-based AR systems are a good option here, as one can easily introduce excellent color graphics with them, and a potentially lower-quality video image is of lesser importance.

4.6 Concluding Remarks and Outlook

We have described medical AR as a form of advanced surgical image guidance. It enables physicians to look beyond the surface of the patient, and see anatomy and instruments that would otherwise be hidden from direct view. Standard image guidance systems provide essentially the same information, but removed from the patient. AR visualization includes this patient context and allows the physician to focus on the surgical site where all supporting information now become available. Hand–eye coordination becomes more straightforward, and understanding of the 3D topology becomes easier. However, AR comes at the price of added calibration and tracking complexity.

An important question is whether AR also provides a corresponding increase in clinical value. There is, of course, no general answer. It depends on the particular surgical or interventional procedure. At the current time, even though there are a variety of commercial surgical navigation systems on the market, none of them has an AR visualization option. The question about the actual clinical value of medical AR is still an open and important question.

To advance AR in general, two areas in particular will require more attention. AR perception studies [Johnson et al. 2002; Lerotic et al. 2007] will help to better understand how to fuse real and virtual images in an optimal way so that they register correctly in the user's brain. AR usability studies will help to better understand the potential user benefits of AR visualization in comparison to other visualization approaches. For medical AR, however, one needs to build medical AR prototypes and evaluate them in collaboration with clinicians to ultimately answer the question about its value as a clinical tool.

Building a basic AR system has become relatively easy. Hardware components, and in particular tracking systems, are available off the shelf. Computers have reached a performance level that makes real-time AR visualization possible in a straightforward way. Software modules for a variety of AR-related functions can be downloaded for reuse from the Internet, notably from the AR-toolkit [Billinghurst and Kato 1999; HITLab 2007] and ARTag [Fiala 2004]. In addition, the literature listed in this chapter's bibliography contains many of the technical details on how to design and test AR systems.

On the other hand, simply building a basic AR system is unlikely to make an impact on the field of medical AR. For clinical evaluation, a well-engineered system, not only with accurate and robust tracking, good display, and convincing visualization is required, but, importantly, one that also fits into the clinical environment, supports a smooth data transfer, and provides an efficient workflow. Anybody interested in medical AR research should be aware of this hurdle: it may be easy to get started, but it is a substantial effort to develop a clinically meaningful AR system. Evaluation of a prototype system will be an evaluation of the AR concept as much as an evaluation of the particular implementation. Without a convincing implementation, the clinician may develop a negative bias toward the whole AR concept, or at least quickly lose interest in further tests.

To make medical AR successful, one needs to pick the right applications (and let clinical requirements determine the design choices). If the clinical task is too simple, AR guidance may just be unnecessary. If the clinical task is truly challenging, the physician can appreciate the support of the AR system. Then the AR system needs also to provide value beyond that of a standard image guidance system. Our main expectation is that AR can be shown to be the more ergonomic tool and permit an easier, more efficient workflow.

AR is in fact entering clinical practice unobtrusively. The company, Carl Zeiss Inc. (Thornwood, NY) offers a surgical microscope MultiVision™, with image overlay [http://www.meditec.zeiss.com]. Here the physicians do not need to be introduced to new equipment, but they receive increased functionality and value from existing tools. Other types of medical AR will follow, driven by prior demonstration of their clinical value. Endoscopy-based AR systems also may not require a change in instrumentation for the user, and conventional navigation systems could easily be equipped with AR as a high-end visualization option. There are no real technical barriers to build practical medical AR systems. The bottleneck is primarily the current lack of a market driver, and the amount of effort and resources required to develop and prove a practical medical AR system. Ultimately, medical AR promises practical, easy-to-use tools, with applications not only in interventional image guidance, but also in training and education [Sielhorst et al. 2004a]. The field is sufficiently exciting that it should continue, turning the promises into real systems.

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