Advanced Medical Displays: A Literature Review of Augmented Reality

Tobias Sielhorst, Marco Feuerstein, and Nassir Navab

***Abstract*—The impressive development of medical imaging technology during the last decades provided physicians with an increasing amount of patient specific anatomical and functional data. In addition, the increasing use of non-ionizing real-time imaging, in particular ultrasound and optical imaging, during surgical procedures created the need for design and development of new visualization and display technology allowing physicians to take full advantage of rich sources of heterogeneous preoperative and intraoperative data. During 90's, medical augmented reality was proposed as a paradigm bringing new visualization and interaction solutions into perspective. This paper not only reviews the related literature but also establishes the relationship between subsets of this body of work in medical augmented reality. It finally discusses the remaining challenges for this young and active multidisciplinary research community.**

I. Introduction

MEDICAL augmented reality takes its main motivation from the need of visualizing medical data and the patient within the same physical space. It goes back to the vision of having x-ray vision, seeing through objects. This would require real-time in-situ visualization of co-registered heterogeneous data, and was probably the goal of many medical augmented reality solutions proposed in literature. As early as 1938, Steinhaus [1] suggested a method for visualizing a piece of metal inside tissue registered to its real view even before the invention of computers. The method was based on the geometry of the setup and the registration and augmentation was guaranteed by construction. In 1968, Sutherland [2] suggested a tracked head-mounted display as a novel human-computer interface enabling viewpoint-dependent visualization of virtual objects. His visionary idea and first prototype were conceived at a time when computers were commonly controlled in batch mode rather than interactively. It was only two decades later that the advances in computer technology allowed scientists to consider such technological ideas within a real-world application. It is interesting to note that this also corresponds to the first implementation of a medical augmented reality system proposed by Roberts *et al.* [3] in 1986. They developed a system integrating segmented computed tomography (CT) images into the optics of an operating microscope. After an initial interactive CT-to-patient-registration, movements of the operating microscope were measured using an ultrasonic tracking system. Early 1990s augmented reality was also considered for other applications including industrial assembly [4], paperless office [5], and machine maintenance [6].

While virtual reality (VR) aimed at immersing the user entirely into a computer-generated virtual world, augmented reality (AR) took the opposite approach, in which virtual computer generated objects were added to the real physical world [7]. Within their so-called virtuality continuum [8], Milgram and Kishino described AR as a mixture of virtual reality (VR) and the real world in which the real part is more dominant than the virtual one. Azuma described AR by its properties of aligning virtual and real objects, and running interactively and in real-time [9], [10].

In augmented reality inheres the philosophy that intelligence amplification (IA) of a user has more potential than artificial intelligence (AI) [11], because human experience and intuition can be coupled by the computational power of computers.

II. Overview of Medical AR Systems and Technologies

The first setup augmenting imaging data registered to an object was described in 1938 by the Austrian mathematician Steinhaus [1]. He described the geometric layout to reveal a bullet inside a patient with a pointer that is visually overlaid on the invisible bullet. This overlay was aligned by construction from any point of view and its registration works without any computation. However, the registration procedure is cumbersome and it has to be repeated for each patient. The setup involves two cathodes that emit X-rays projecting the bullet on a fluoroscopic screen (see Fig. 2). On the other side of the X-ray screen, two spheres are placed symmetrically to the X-ray cathodes. A third sphere is fixed on the crossing of the lines between the two spheres and the two projections of the bullet on the screen. The third sphere represents the bullet. Replacing the screen with a semi-transparent mirror and watching the object through the mirror, the third sphere is overlaid exactly on top of the bullet from any point of view. This is possible because the third sphere is at the location to which the bullet is mirrored. Therefore, the setup yields stereoscopic depth impression. The overlay is restricted to a single point and the system has to be manually calibrated for each augmentation with the support of an X-ray image with two X-ray sources.

In the next decades, different technologies followed that allow for medical augmentation of images. This section will introduce them as seven fundamental classes, including their specific limitations and advantages. Each subsection begins with the definition of the respective category. Fig. 15 gives a short overview on these technologies.

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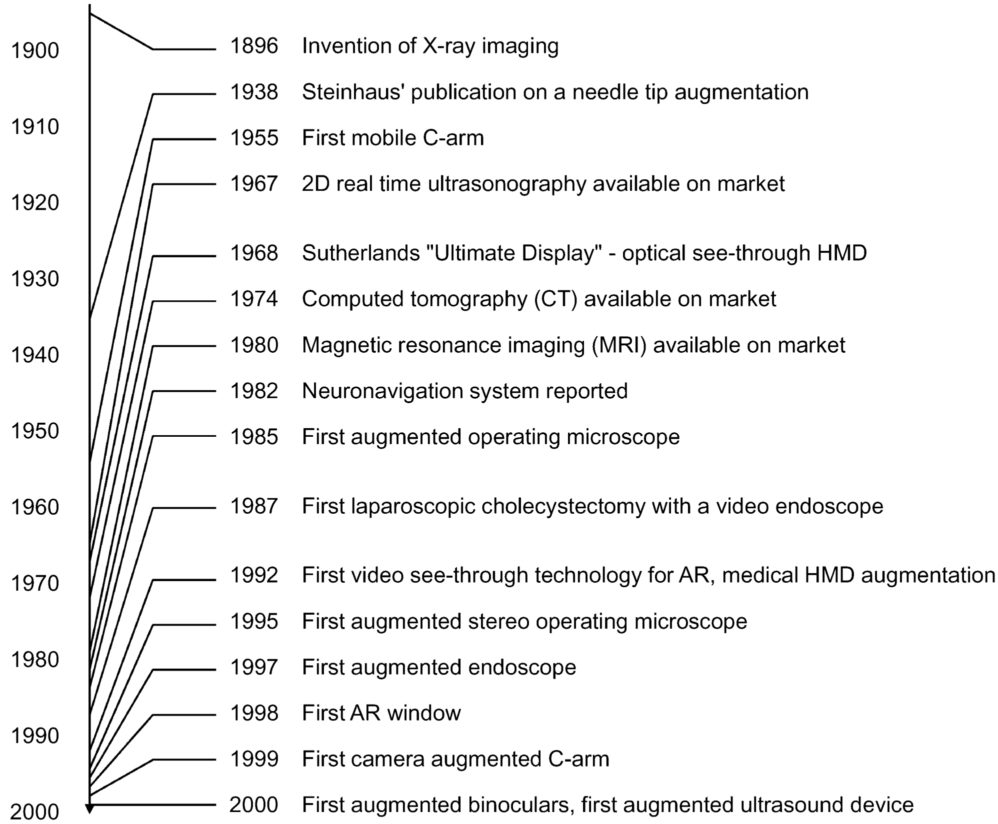


Fig. 1. Inventions timeline of selected imaging and AR technology [2] © 1968 IEEE.

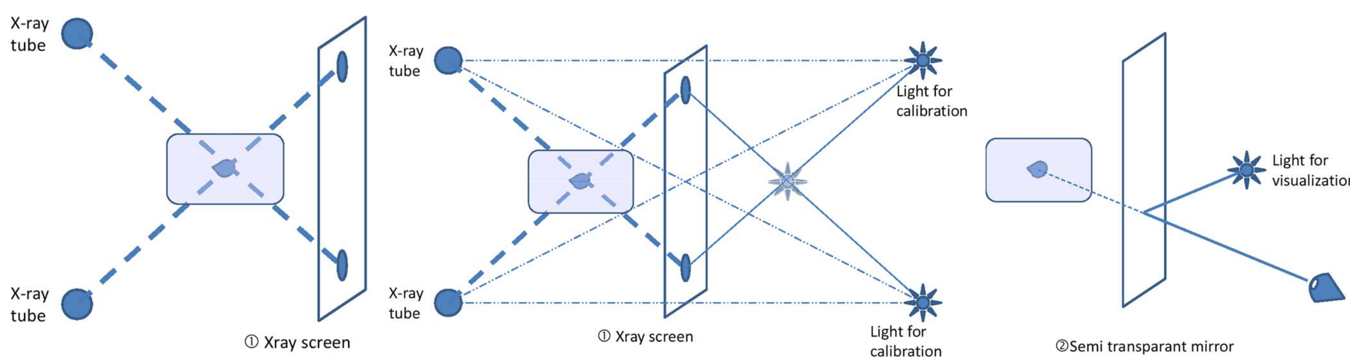


Fig. 2. Early suggestion for overlay of imaging data by Steinhaus [1] in 1938. Computation-free calibration (left and middle) and visualization (right) of the proposed setup.

We start with devices that allow for in-situ visualization. This means that the view is registered to the physical space.

A. *HMD Based AR System*

The first head-mounted display (HMD)-based AR system was described by Sutherland [2] in 1968 (see Fig. 3). A stereoscopic monochrome HMD combined real and virtual images by means of a semi-transparent mirror. This is also referred to as optical see-through HMD. The tracking was performed mechanically. Research on this display was not application driven, but aimed at the "ultimate display" as Sutherland referred to it.

Bajura *et al.* [12] reported in 1992 on their video see-through system for the augmentation of ultrasound images (see Fig. 4). The system used a magnetic tracking system to determine the pose of the ultrasound probe and HMD. The idea of augmenting live video instead of optical image fusion appears counterproductive at first sight since it reduces image quality and introduces latency for the real view. However, by this means the real view can be controlled electronically resulting in the following advantages:

1) No eye-to-display calibration is needed, only the camera-to-tracker transformation has to be calculated, which may remain fixed.
2) Arbitrary merging functions between virtual and real objects are possible as opposed to brightening up the real view by virtual objects in optical overlays. Only video overlay allows for opaque virtual objects, dark virtual objects, and correct color representation of virtual objects.
3) By delaying the real view until the data from the tracking system is available, the *relative* lag between real and virtual

Fig. 3. The first (optical see-through) HMD by Sutherland [2].

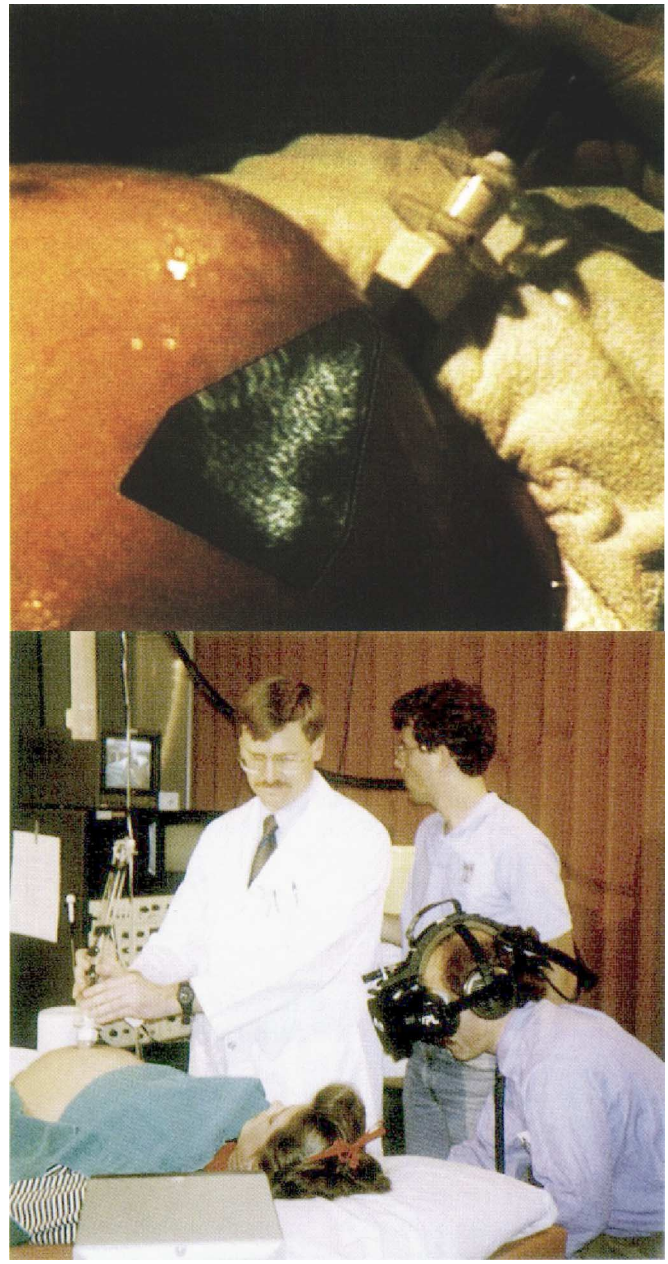


Fig. 4. First video see-through HMD: Augmentation of ultrasound slices [12]. © 1992 ACM.

objects can be eliminated as described by Bajura *et al.* [13] and Jacobs *et al.* [14].

4) For the real view, the image quality is limited by the display specifications in a similar way as it is for the rendered objects. Since the color spectrum, brightness, resolution, accommodation, field of view, etc. are the same for real and virtual objects, they can be merged in a smoother way than for optical overlays.
5) The overlay is not user dependent, since the generation of the augmentation is already performed in the computer, as opposed to the physical overlay of light in the eye. The resulting image of an optical see-through system is in general not known. A validation without interaction is hardly possible with optical overlays.

In 1996, in a continuation of the work of Bajura *et al.* [12], [13], State *et al.* [15] reported on a system with 10 frames per second (fps) creating VGA output. This system facilitates hybrid magnetic and optical tracking and offers higher accuracy and faster performance than the previous prototypes. The speed was mainly limited by the optical tracking hardware. Nowadays, optical tracking is fast enough to be used exclusively. The continued system has been evaluated in randomized phantom studies in a needle biopsy experiment [16]. Users hit the targets significantly more accurately using AR guidance compared to standard guidance.

In 2000, Sauer and colleagues [17] presented a video see-through system that allowed for a synchronized view of real and virtual images in real-time, i.e., 30 fps. In order to ensure that camera images and tracking data are from exactly the same point of time the tracking camera and the video cameras are genlocked, i.e., the tracking system shutter triggers the cameras. Their visualization software waits for the calculated tracking data before an image is augmented. This way, the relative lag is reduced to zero without interpolating tracking data. The system uses inside-out optical tracking, which means that the tracking camera is placed on the HMD to track a reference frame rather than the other way around (see Fig. 5). This way of tracking allows for very low reprojection errors since the orientation of the head can be computed in a numerically more stable way than by outside-in tracking using the same technology [18].

Wright *et al.* [19] reported in 1995 on optical see-through visualization for medical education. The continuation of the system [20] augments anatomical data on a flexible knee joint

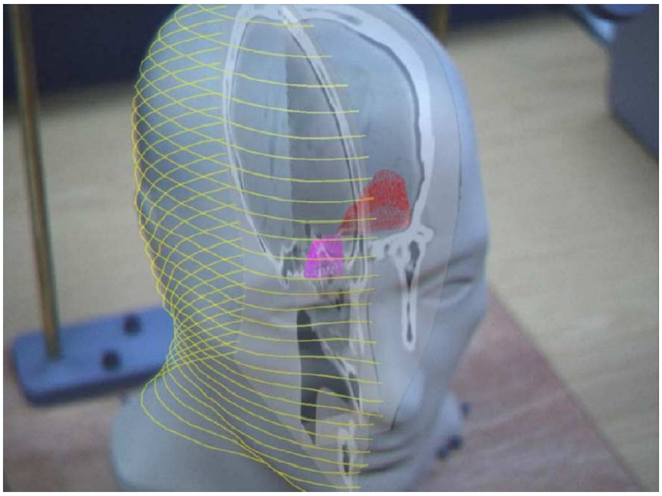


Fig. 5. Video see-through HMD without relative lag [17] © 2000 IEEE.

phantom in order to teach dynamic spatial behavior of anatomy. Our group [21] suggested augmentation of recorded expert motions in regard to a simulator phantom in order to teach medical actions. The system allows for comparative visualization and automatic quantitative comparison of two actions.

Luo and Peli [22] use head mounted display visualization as an aid for visually impaired rather than supporting physicians. They use an optical see-through system to superimpose contour images from an attached camera. The system is meant to help patients with tunnel vision to improve visual search performance.

Rolland and Fuchs [23] discuss in detail advantages and shortcomings of optical and video see-through technology. Cakmaci and Rolland [24] provide a recent and comprehensive overview of HMD designs.

B. Augmented Optics

Operating microscopes and operating binoculars can be augmented by inserting a semi-transparent mirror into the optics. The mirror reflects the virtual image into the optical path of the real image. This allows for high optical quality of real images without further eye-to-display calibration, which is one of the major issues of optical see-through augmentation. Research on augmented optics evolved from stereotaxy in brain surgery in the early 1980s that brought the enabling technology together as for instance described by Kelly [25].

The first augmented microscope was proposed by Roberts *et al.* [3], [26] showing a segmented tumor slice of a computed tomography data set in a monocular operating microscope. This system can be said to be the first operational medical AR system. Its application area was interventional navigation. The accuracy requirement for the system was defined to be 1 mm [27] in order to be in the same range as the CT slice thickness. An average error of 3 mm [27] was measured for reprojection of contours, which is a remarkable result for the first system. However, the ultrasonic tracking did not allow for real-time data acquisition. A change in position of the operating microscope required approximately 20 s for acquiring the new position.

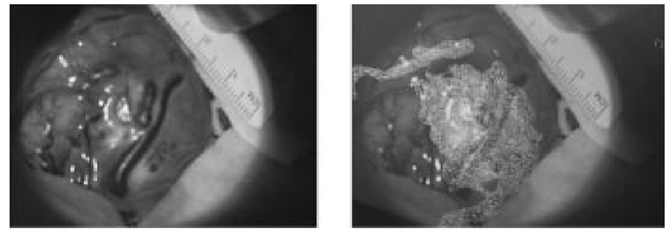


Fig. 6. Augmented microscope: Ordinary and augmented view [29]© 2000 IEEE.

Fig. 7. Augmented binoculars [31] ©2002 IEEE.

In 1995, Edwards *et al.* [28] presented their augmented stereoscopic operating microscope for neurosurgical interventions. It allowed for multicolor representation of segmented 3D imaging data as wireframe surface models or labeled 3D points (see Fig. 6). The interactive update rate of 1–2 Hz was limited by the infrared tracking system. The accuracy of 2–5 mm is in the same range as the system introduced by Friets *et al.* [27]. In 2000, the group reported on an enhanced version [29] with submillimeter accuracy, which was evaluated in phantom studies, as well as clinical studies, for maxillofacial surgery. The new version also allows for calibration of different focal lengths to support variable zoom level settings during the augmentation.

For ophthalmology, Berger *et al.* [30] suggest augmenting angiographic images into a biomicroscope. The system uses no external tracking but image-based tracking, which is possible because the retina offers a relatively flat surface that is textured with visible blood vessel structures. According to the authors, the system offers an update rate of 1–5 Hz and an accuracy of 5 pixels in the digital version of the microscope image.

Birkfellner and colleagues have developed an augmented operating binocular for maxillofacial surgery in 2000 [31], [32] (see Fig. 7). It enables augmentation employing variable zoom and focus as well as customizable eye distances [33]. As opposed to the operating microscopes that are mounted on a swivel arm, an operating binocular is worn by the user.

A drawback of augmented optics in comparison with other augmentation technology is the process of merging real and

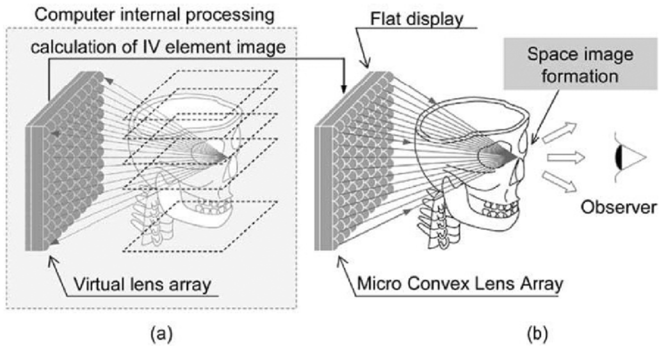


Fig. 8. Concept of integral videography based augmentation and examples [37] ©2004 IEEE.

computed images. As virtual images can only be added and may not entirely cover real ones, certain graphical effects cannot be realized. The impact of possible misperception is discussed in paragraph IV.D. Additionally, the relative lag between the visualization of real and virtual images cannot be neglected for head-worn systems (cf. Holloway [34]).

In addition to the superior imaging quality of the real view, a noteworthy advantage of augmented optics is a seamless integration of its technology into the surgical workflow. The augmented optics can be used as usual if the augmentation is not desired. Furthermore, the calibration or registration routine in the operating room need not be more complicated than for a navigation system.

C. AR Windows

The third type of devices that allows for *in situ* visualization is an AR window. In 1995, Masutani *et al.* [35] presented a system with a semi-transparent mirror that is placed between the user and the object to be augmented. The virtual images are created by an autostereoscopic screen with integral photography technology (see Fig. 8). With microlenses in front of an ordinary screen, different images can be created for different viewing angles. This reduces either the resolution or limits the effective viewing range of the user. However, no tracking system is necessary in this setup to maintain the registration after it has been established once. The correct alignment is independent of the point of view. Therefore, these autostereoscopic AR windows involve no lag when the viewer is moving. The first system could not compute the integral photography dynamically. It had to be precomputed for a certain data set.

In 2002 Liao *et al.* [36], [37] proposed a medical AR window based on integral videography that could handle dynamic scenes. The authors realized the system for a navigation scenario, in which the position of an instrument was supposed to be visualized in the scene. Their algorithm performed the recalculation of a changed image in less than a second.

Blackwell *et al.* [38] presented in 1998 an AR window using a semi-transparent mirror for merging the real view with virtual images from an ordinary monitor. This technology requires tracked shutter glasses for the correct alignment of augmented objects and stereo vision, but it can handle dynamic images for navigation purposes at a high resolution and update rate.

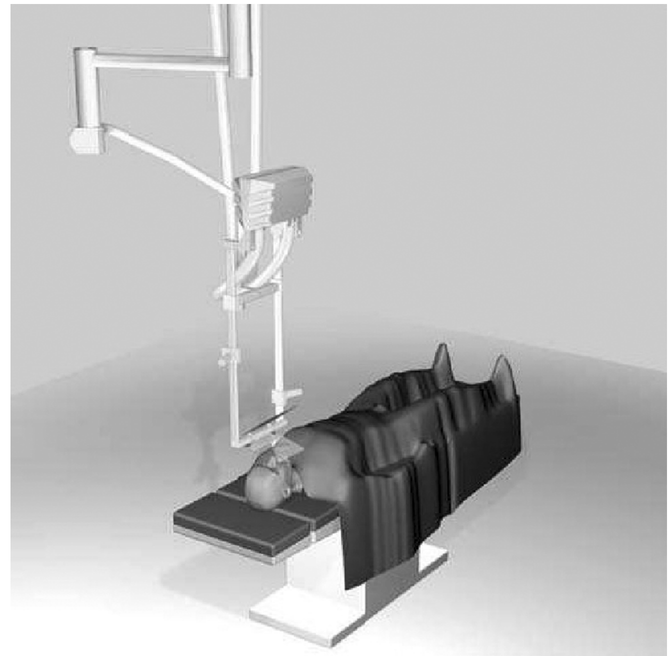


Fig. 9. AR window that needs polarization glasses [39] ©2003 IEEE.

For *in situ* visualization, AR windows seem to be a perfect match to the operating room at first sight. For ergonomic and sterility reasons it is a good idea not to make surgeons wear a display. There are different ways of realizing AR windows. In detail, each one introduces a trade-off: Autostereoscopic displays suffer from poorer image quality in comparison with other display technologies. In principle, they offer a visualization for multiple users. However, this feature introduces another trade-off regarding image quality.

Display technology using shutter glasses needs cables for trigger signals and power supply. Polarization glasses, as for instance used in the system introduced by Goebbels *et al.* [39], do not need cables and weigh less than an HMD, but limit the viewing angle of the surgeon to match the polarization. Non-autostereoscopic AR windows need to track the position of the user's eye in addition to the position of the patient and the AR window. This introduces another source of error.

Wesarg *et al.* [40] suggest a monoscopic AR window based on a transparent display. The design offers a compact setup, since no mirror is used, and no special glasses are required. However, it cannot display stereoscopic images and only one eye can see a correct image overlay. Since no mirror is used, the foci of the virtual and real image are at completely different distances.

All AR window designs have to take care of distracting reflections from different light sources. Last but not least, the display must be placed between the patient and the viewer. This may obstruct the surgeons' working area.

We believe that an optimal in-situ visualization device could consist of combination of an AR window and an HMD; an example may be an HMD attached to a boom.

D. Augmented Monitors

In this section, we cluster all systems that augment video images on ordinary monitors. The point of view is defined by an additional tracked video camera. In 1993, Lorensen and Kikinis [41] published their live video augmentation of segmented MRI data on a monitor. This initial system did not include tracking of the video camera yet. The camera-to-image registration had to be performed manually. The successor of this setup included a vision-based tracking system with fiducial markers [42].

Sato *et al.* [43] visualize segmented 3D ultrasound images registered to video camera images on a monitor for image guidance of breast cancer surgery. Nicolau *et al.* [44] describe a camera-based AR system using markers that are detected in the camera image. The system aims at minimally invasive liver ablation.

As an advantage of augmented monitors, users need not wear an HMD or glasses. By definition, augmented monitors do not however, offer in situ visualization nor stereoscopic vision. Using them adds a tracked camera to the clinical setup.

E. Augmented Endoscopes

A separate paragraph is dedicated to endoscope augmentation although it might be considered as a special case of monitor-based augmented reality or augmented imaging devices (see Section II-F). In contrast to augmented imaging devices endoscopic images need a tracking system for augmentation. As opposed to monitor-based AR the endoscopic setup already contains a camera. Hence, the integration of augmented reality techniques does not necessarily introduce additional hardware into the workflow of navigated interventions. A lot of investigative work has been carried out that dealt specifically with endoscopic augmentation.

The first usage of endoscopes as telescopic instruments utilizing a light source dates back to the 19th century. Endoscopy was mainly dedicated to diagnosis until the invention of video-based systems in the 1980s. Video endoscopy permits different team members to see the endoscopic view simultaneously. With this approach, it is possible for an assistant to position the endoscope while the operating surgeon can use both hands for the procedure. This feature opened the field of endoscopic surgeries. The removal of the gallbladder was one of the first laparoscopic surgeries. This operation also became a standard minimally invasive procedure. Since then, endoscopy has been successfully introduced into other surgical disciplines. Comprehensive literature reviews on the history of endoscopy can be found, for instance, in [45], [46], and [47].

Although endoscopic augmentation seems to be a straightforward step it has been realized as recently as the end of the 1990s by Freysinger *et al.* [48] for ear, nose and throat (ENT) surgery and Shahidi and colleagues [49] for brain surgery. Fig. 10 shows a visualization of the latter system including a targeting help in the endoscope image. Scholz *et al.* presented a navigation system for neurosurgery based on processed images [50]. Shahidi and Scholz use infrared tracking technology and a rigid endoscope while Freysinger's system uses magnetic tracking.

Mourgues *et al.* [51] describe endoscope augmentation in a robotic surgery system. The tracking is done implicitly by the robot since the endoscope is moved by the robot's arm. Therefore no additional tracking system is necessary.

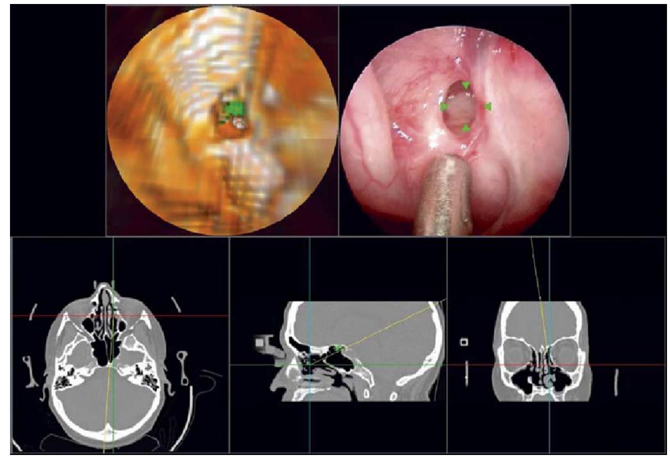


Fig. 10. Augmentation in an endoscope [55] ©2002 IEEE.

For endoscopic augmentation, the issues of calibration, tracking, and visualization are partly different than for other types of AR devices:

1) Calibration and Undistortion of Wide Angle Optics: Because of their wide-angle optics, endoscopes suffer from a noticeable image distortion. If a perfect, distortion-free pinhole camera model is assumed for superimposition, a particular source of error in the augmented image will be introduced [52]. This issue can be neglected in other AR systems with telephoto optics. Common types of distortion are radial distortion (also referred to as barrel distortion) and tangential distortion. Either the endoscope image has to be undistorted or the rendered overlay has to be distorted to achieve a perfect superimposition. While first approaches [53] required several minutes to undistort a single endoscope image, this process can now be completed in real-time: De Buck *et al.* [54] undistort sample points in the image and map a texture of the endoscope image on the resulting tiles; Shahidi *et al.* [55] precompute a look-up table (LUT) for each pixel for real-time undistortion.

In order to model the geometry of an endoscope camera, the intrinsic camera parameters focal length and principal point need to be determined. This can be achieved using well-established camera calibration techniques [56]–[58]. Most systems assume the focal length of an endoscope camera to be kept constant, although many endoscopes incorporate zoom lenses to change it intraoperatively, invalidating a certain calibration. Stoyanov *et al.* suggest to automatically adjust the calibration for intraoperative changes of the focal length of a stereoscopic camera [59]. Even though models for the calibration of monoscopic cameras with zoom lenses exist [60], they are not easily applicable to endoscopes. These models require the (preferably automatic) determination of the physical ranges for the lens settings e.g., in terms of motor units. However, the zoom settings of endoscopes are usually adjusted manually, rather than by a precise motor.

To obtain a rigid transformation from the camera coordinate frame to the coordinate frame of an attached tracking body or sensor, most authors employ hand-eye calibration techniques [51], [61]–[64]. An alternative approach makes use of a tracked

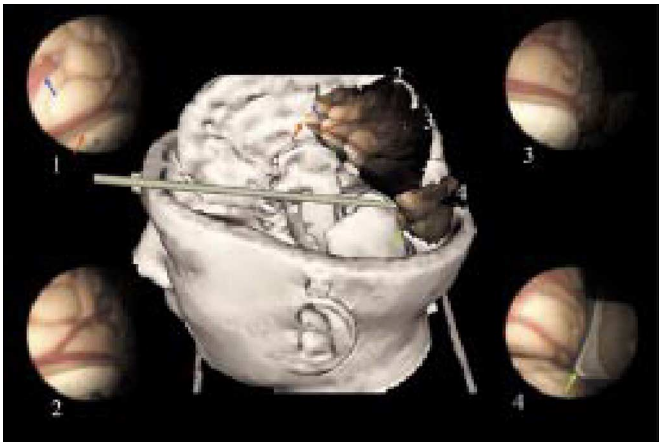


Fig. 11. Context sensing by texturing segmented model. [75] ©2002 IEEE.

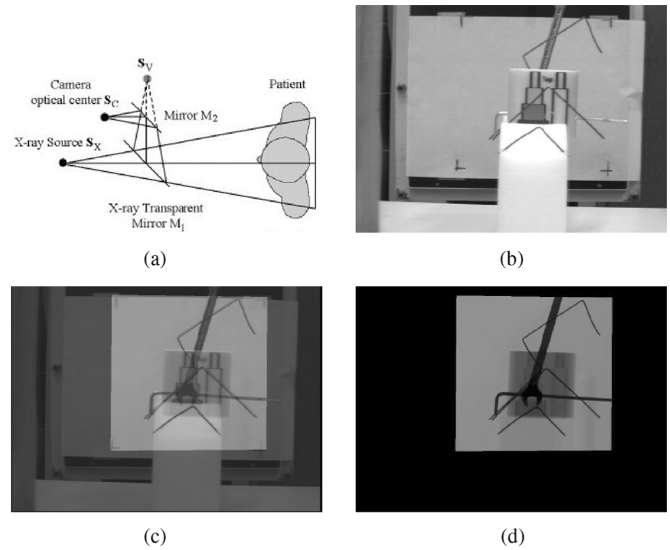


Fig. 12. Camera-augmented c-arm (CamC) [78]. © 1999 IEEE. (a) Principle of CamC (CamC), (b) Camera image, (c) fused image, (d) Fluoroscopic X-ray image.

calibration pattern, whose physical coordinates are known with respect to the tracker [54], [55], [65].

In certain applications oblique-viewing endoscopes are used, for which the viewing directions are changeable by rotating the scope cylinder. Yamaguchi *et al.* [66] and De Buck *et al.* [67] developed calibration procedures for such endoscopes.

2) Tracking of Flexible Endoscopes: Non-rigid endoscopes cannot be tracked by optical tracking systems. Bricault *et al.* [68] describe the registration of bronchoscopy and virtual bronchoscopy images using only geometric knowledge and image processing. The algorithms employed did not have real-time capability, however, they proved to be stable when used on recorded videos. In contrast to Bricault's shape from shading approach, Mori *et al.* [69] use epipolar geometry for image processing. In order to improve the performance of their registration algorithm they suggest the addition of electromagnetic tracking of the bronchoscope [70]. To achieve a fusion of the bronchoscopic video with a target path, Wegner *et al.* restrict electromagnetic tracking data onto positions inside a previously segmented bronchial tree [71]. Some groups, for instance Klein *et al.* [72], use electromagnetic tracking exclusively.

3) Endoscopy Related Visualization Issues: The augmentation of endoscopic data does not only entail fusion with other imaging data. Konen *et al.* [50] suggest several image-based methods with a tracked endoscope to overcome typical limitations, such as replay of former images in case of loss of sight, image mosaicing, landmark tracking, and recalibration with anatomical landmarks. Krueger *et al.* [73] evaluate endoscopic distortion correction, color normalization, and temporal filtering for clinical use.

One of the reasons for augmenting endoscope images is to provide the anatomical context since the point of view and the horizon are changing. Recovering each of these issues requires a heightened level of concentration from surgeons since their field of view is very limited and the operating surgeon generally does not move the endoscope personally. Fuchs *et al.* [74] suggest provision of anatomical context by visualizing laparoscopic images *in situ* with a head-mounted display. The necessary three-dimensional model of the surface as seen by the laparoscope is created with a pattern projector. Dey *et al.* [75] project endoscope images on segmented surfaces for providing context and creating endoscopic panorama images (see Fig. 11). Kawamata *et al.* [76] visualize the anatomical context by drawing virtual objects in a larger area of the screen than endoscope images are available. Ellsmere and colleagues [77] suggest augmenting laparoscopic ultrasound images into CT slices and using segmented CT data for improved context sensing.

F. Augmented Medical Imaging Devices

Augmented imaging devices can be defined as imaging devices that allow for an augmentation of their images without a tracking system. The alignment is guaranteed by their geometry.

A construction for the overlay of fluoroscopic images on the scene has been proposed by Navab *et al.* [78] in 1999 (see Fig. 12). An ordinary mirror is inserted into the X-ray path of a mobile C-arm[1]. By this means it is possible to place a video camera that records light following the same path as the X-rays. Thus it is possible to register both images by estimating the homography between them without spatial knowledge of the objects in the image. The correct camera position is determined once during the construction of the system. For image fusion, one image can be transformed electronically to match the other using the estimated homography. The system provides augmented images without continuous X-ray exposure for both patient and physician. The overlay is correct until the patient moves relative to the fluoroscope. A new X-ray image has to be taken in such a case.

Tomographic reflection is a subgroup of augmented imaging devices. In 2000, Masamune and colleagues [79], [80] proposed an image overlay system that displays CT slices in-situ. A semi-transparent mirror allows for a direct view on the patient as well as a view on the aligned CT slice (see Fig. 13). The viewer may move freely while the CT slice remains registered without any

[1]C-arm: Medically widespread X-ray imaging device with a C-shaped gantry

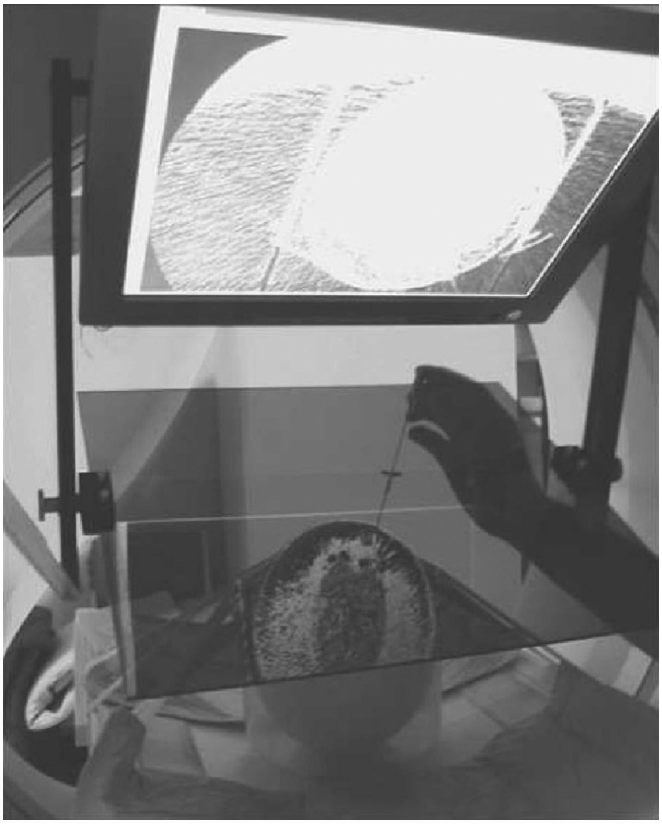


Fig. 13. CT reflection [79]: Concept and prototypical setup. © 2005 IEEE.

tracking. The overlaid image is generated by a screen that is placed on top of the imaging plane of the scanner. The semi-transparent mirror is placed in the plane that halves the angle between the slice and the screen. The resulting overlay is correct from any point of view up to a similarity transform that has to be calibrated during the construction of the system. The system is restricted to a single slice per position of the patient. For any different slice, the patient has to be moved on the bed. Fischer *et al.* [81] have extended this principle to magnetic resonance imaging.

A similar principle has been applied to create an augmented ultrasound echography device. Stetten *et al.* [82], [83] proposed in 2000 the overlay of ultrasound images on the patient with a semi-transparent mirror and a little screen that is attached to the ultrasound probe (see Fig. 14). The mirror is placed on the plane that halves the angle between the screen and the B-scan plane of ultrasonic measurements. Similarly to the reflection of CT or MRI slices, it allows for *in situ* visualization without tracking. In addition to real-time images, it allows for arbitrary slice views, as the ultrasound probe can be freely moved.

G. Projections on the Patient

Lastly, we present systems augmenting data directly onto the patient. The advantage of these systems is that the images are generally visible *in situ* without looking through an additional device such as glasses, HMD, microscope, loupes, etc. As another beneficial feature, the user need not be tracked if visualization is meant to be on the skin rather than beneath. This also

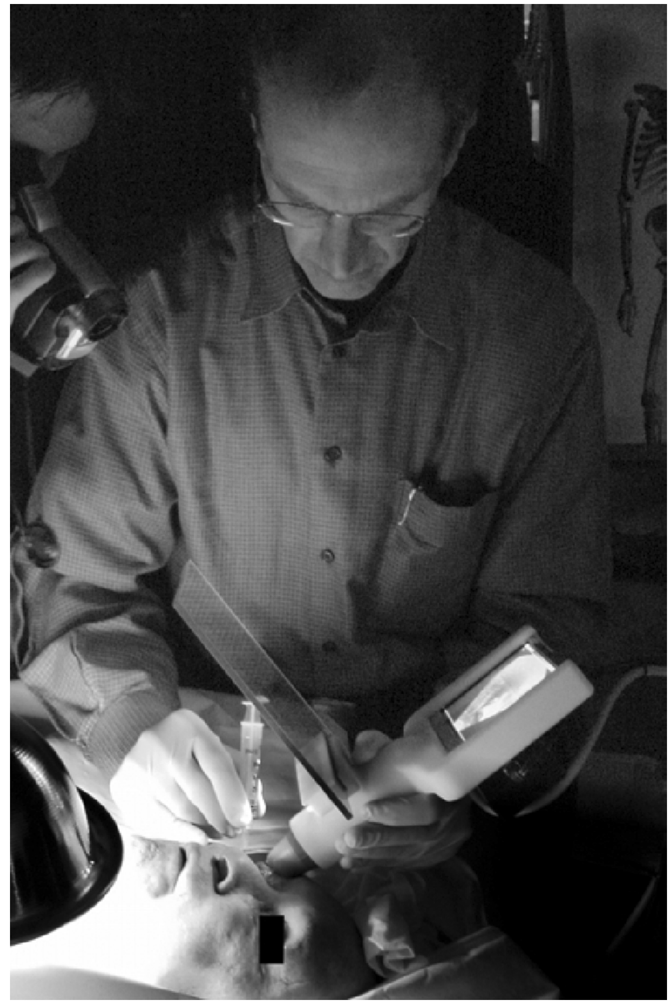


Fig. 14. Ultrasound augmentation by tomographic reflection: Sonic Flashlight [82], [83] ©2000 IEEE.

means that such a visualization can be used for multiple users. The simplicity of the system introduces certain limitations as a compromise, though.

Glossop *et al.* [84] suggested in 2003 a laser projector that moves a laser beam into arbitrary directions by means of controlled mirrors. Trajectories of the laser appear as lines due to the persistence of vision effect. The images are limited to a certain number of bright monochrome lines or dots and non-raster images. The system also includes an infrared laser for interactive patient digitization.

Sasama *et al.* [85] use two lasers for mere guidance. Each of these lasers creates a plane by means of a moving mirror system. The intersection of both planes is used to guide laparoscopic instruments in two ways. The intersecting lines or the laser on the patient mark the spot of interest, for instance an incision point. The laser planes can also be used for determining an orientation in space. The system manipulates the two laser planes in such a way that their intersecting line defines the desired orientation. If both lasers are projected in parallel to the instrument, the latter has the correct orientation. The system can only guide instruments to points and lines in space but it cannot show contours or more complex structures.

	HMD based	Augmented optics	AR windows	Augmented monitors	Augmented endoscopes	Tomographic reflection	Projection on the patient
Improved hand eye coordination	x	x	x			x	x
Extra value from image fusion	x	x	x	x	x	x	x
Implicit 3D interaction	x	x	x				
Stereoscopic visualization	x	x	x		in rare cases	only in plane	
Multiuser capability	additional AR device	additional AR device	limited	x	x	x	limited

Fig. 15. Simplified relationship between technology and potential benefits. Grey color indicates *in situ* visualization.

III. Potential Benefits of AR Visualization

The crucial question regarding new visualization paradigms is "What can it do for us that established technology cannot?". AR provides an intuitive human computer interface. Since intuition is difficult to measure for an evaluation we subdivide the differences between AR and ordinary display technology in this section into four phenomena: Image fusion, 3D interaction, 3D visualization, and hand-eye coordination. Fig. 15 depicts a simplified relationship between these phenomena and AR technology.

A. Extra Value From Image Fusion

Fusing registered images into the same display offers the best of two modalities in the same view.

An extra value provided by this approach may be a better understanding of the image by visualizing anatomical context that has not been obvious before. This is the case for endoscopic camera and ultrasound images, where each image corresponds only to a small area. (See paragraph II.E.3)

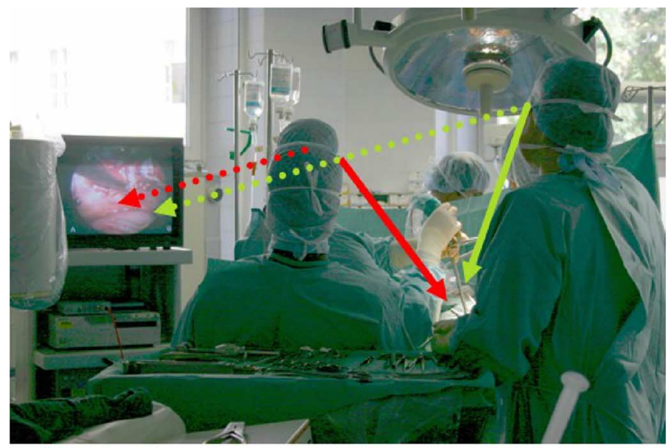
Another example for additional value is displaying two physical properties in the same image that can only be seen in either of the modalities. An example is the overlay of beta probe activity. Wendler *et al.* [86] support doctors by augmenting previously measured activity emitted by radioactive tracers on the live video of a laparoscopic camera. By this means, physicians can directly relate the functional tissue information to the real view showing the anatomy and instrument position.

A further advantage concerns the surgical workflow. Currently, each imaging device introduces another display into the operating room [see Fig. 16(b)] thus the staff spends valuable time on finding a useful arrangement of the displays. A single display integrating all data could solve this issue. Each imaging device also introduces its own interaction hardware and graphical user interface. A unified system could replace the inefficient multitude of interaction systems.

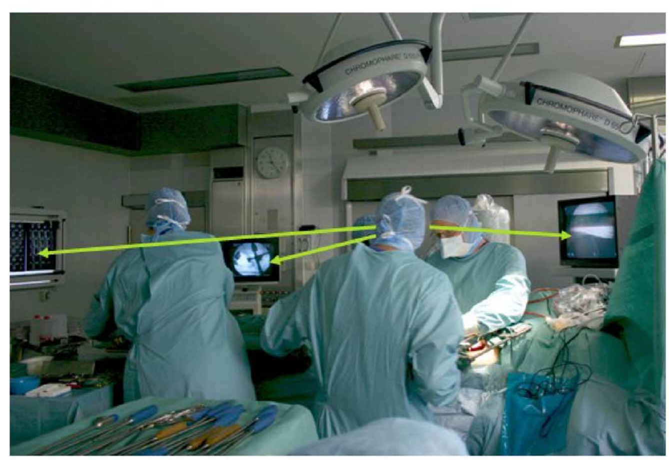
B. Implicit 3D Interaction

Interaction with 3D data is a cumbersome task with 2D displays and 2D interfaces (cf. Bowman [87]). Currently, there is no best practice for three-dimensional user interfaces as opposed to 2D interfaces using the WIMP paradigm (windows, icons, menus, and pointing).

AR technology facilitates implicit viewpoint generation by matching the viewport of the eye/endoscope on real objects to the viewport on virtual objects. Changing the eye position relative to an object is a natural approach for 3D inspection.



(a)



(b)

Fig. 16. Current minimally invasive spine surgery setup at "'Chirurgische Klinik'", hospital of Ludwigs-Maximilian Universität München. (a) Action takes place on a very different position than the endoscope display. (b) Each imaging device introduces another display.

3D user interfaces reveal their power only in tasks that cannot be easily reduced to two dimensions, because 2D user interfaces benefit from simplification by dimension reduction and the fact that they are widespread. Recent work by Traub *et al.* [88] suggests that navigated implant screw placement is a task that can benefit from 3D user interaction, as surgeons were able to perform drilling experiments faster with *in situ* visualization compared to a navigation system with a classic display. Although the performance speed is probably not a valid metric for a medical drilling task, the experiments indicate that the surgeons had a faster mental access to the spatial situation.

C. 3D Visualization

Many augmented reality systems allow for stereoscopic data representation. Stereo disparity and motion parallax due to viewpoint changes (see Section III-B) can give a strong spatial impression of structures.

In digital subtraction angiography, stereoscopic displays can help doctors to analyze the complex vessel structures [89]. Calvano *et al.* [90] report on positive effects of the stereoscopic view provided by a stereo endoscope for in-utero surgery. The enhanced spatial perception may be also useful in other fields.

D. Improved Hand-Eye Coordination

A differing position and orientation between image acquisition and visualization may interfere with the hand-eye coordination of the operating person. This is a typical situation in minimally invasive surgery [see Fig. 16(a)]. Hanna *et al.* [91] showed that the position of an endoscope display has a significant impact on the performance of a surgeon during a knotting task. Their experiments suggest the best positions of the display to be in front of the operator at the level of his or her hands.

Using *in situ* visualization, there is no offset between working space and visualization. No mental transformation is necessary to convert the viewed objects to the hand coordinates.

IV. Current Issues

We have presented different systems in this paper with their history and implications. In this section we present current limiting factors for most of the presented types and approaches to solve them.

A. Registration, Tracking, and Calibration

The process of registration is the process of relating two or more data sets to each other in order to match their content. For augmented reality the registration of real and virtual objects is a central piece of the technology. Maintz and Viergever [92] give a general review about medical image registration and its subclassification.

In the AR community the term tracking refers to the pose estimation of objects in real time. The registration can be computed using tracking data after an initial calibration step that provides the registration for a certain pose. This is only true if the object moves but does not change. Calibration of a system can be performed by computing the registration using known data sets, e.g., measurements of a calibration object. Tuceryan *et al.* [93] describe different calibration procedures that are necessary for video augmentation of tracked objects. These include image distortion determination, camera calibration, and object-to-fiducial calibration.

Tracking technology is one of the bottlenecks for augmented reality in general [10]. As an exception, this is quite different for medical augmented reality. In medical AR, the working volume and hence the augmented space is indoors, predefined, and small. Therefore, the environment, i.e., the operating room, can be prepared for the augmented reality system. Optical (infrared) tracking systems are already in use in modern operating rooms for intraoperative navigation. In orthopedics, trauma surgery, and neurosurgery, which only require a rigid body registration, available navigation systems proved to be sufficiently accurate. King *et al.* [29] proved in clinical studies to have overall errors in the submillimeter range for their microscope based augmented reality system for neurosurgery. For the pose determination of the real view infrared tracking is currently the best choice. Only augmented flexible endoscopes have to use different ways of tracking [see Section II-E2)].

As the last piece in the alignment chain of real and virtual there is the patient registration. The transformation between image data and patient data in the tracking coordinate system has to be computed. Two possibilities may apply:

1) Rigid Patient Registration: Registration algorithms are well discussed in the community. Their integration into the surgical workflow requires mostly a trade off between simplicity, accuracy, and invasiveness.

Registration of patient data with the AR system can be performed with fiducials that are fixed on the skin or implanted [94]. These fiducials must be touched with a tracked pointer for the registration process. Alternatively, the fiducials can be segmented in the images of a tracked endoscope rather than touching them with a tracked pointer for usability reasons. Whereas Stefansic *et al.* propose the direct linear transform (DLT) to map the 3D locations of fiducials into their corresponding 2D endoscope images [95], Feuerstein *et al.* suggest a triangulation of automatically segmented fiducials from several views [96], [97]. Baumhauer *et al.* study different methods for endoscope pose estimation based on navigation aids stuck onto the prostate and propose to augment 3D transrectal ultrasound data on the camera images [98]. Using this method, no external tracking system is needed.

Especially for maxillofacial surgery, fiducials can be integrated in a reproducibly fixed geometry [29]. For spine surgery, Thoranaghatte *et al.* try to attach an optical fiducial to the vertebrae and use the endoscope to track it *in situ* [99].

Point-based registration is known to be a reliable solution in principle. However, the accuracy of a fiducial-based registration varies on the number of fiducials and quality of measurement of each fiducial, but also on the spatial arrangement of the fiducials [100].

Another approach is to track the imaging device and register the data to it. This procedure has the advantage that no fiducials have to be added to the patient while preserving high accuracy. Grzeszczuk *et al.* [101] and Murphy [102] use a fluoroscope to acquire intraoperative X-ray images and register them to digitally reconstructed radiographs (DRR) created from preoperative CT. This 2D–3D image registration procedure, which could also be used in principle for an AR system, has the advantage that no fiducials have to be added to the patient while keeping high accuracy. By also tracking the C-arm, its subsequent motions can be updated in the registered CT data set.

Feuerstein *et al.* [97], [103] augment 3D images of an intraoperative flat panel C-arm into a laparoscope. This approach is sometimes also called registration-free [104], because doctors need not perform a registration procedure. As a drawback such an intrinsic registration is only valid as long as the patient does not move after imaging.

Grimson *et al.* [42] follow a completely different approach by matching surface data of a laser range scanner to CT data of the head. For sinus surgery, Burschka *et al.* propose to reconstruct 3D structures using a non-tracked monocular endoscopic camera and register them to a preoperative CT data set [105]. For spine surgery, Wengert *et al.* describe a system that uses a tracked endoscope to achieve the photogrammetric reconstruction of the surgical scene and its registration to preoperative data [106].

2) Deformable Tissue: The approaches mentioned above model the registration of a rigid transformation. This is useful for the visualization before an intervention and for a visualization of not deformed objects. The implicit assumption of a rigid structure is correct for bones and tissue exposed to the same forces during registration and imaging, but not for soft tissue deformed by, e.g., respiration or heart beat.

A well known example breaking this assumption is the brain shift in open brain surgery. Maurer *et al.* [107] show clearly that the deformation of the brain after opening the skull may result in misalignment of several millimeters.

There are three possible directions to handle deformable anatomy.

1) Use very recent imaging data for a visualization that includes the deformation. Several groups use ultrasound images that are directly overlayed onto the endoscopic view [108]–[110].
2) Use very recent data to update a deformable model of the preoperative data. For instance Azar *et al.* [111] model and predict mechanical deformations of the breast.
3) Make sure that the same forces are exposed to the tissue. Active breathing control is an example for compensating deformations due to respiration [112], [113].

Baumhauer *et al.* [114] give a recent review on the perspectives and limitations in soft tissue surgery, particularly focusing on navigation and AR in endoscopy.

B. Time Synchronization

Time synchronization of tracking data and video images is an important issue for an augmented endoscope system. In the unsynchronized case, data from different points of time would be visualized. Holloway *et al.* [34] investigated the source of errors for augmented reality systems. The errors of time mismatch can raise to be the highest error sources when the camera is moving. To overcome this problem, Jacobs *et al.* [14] suggest methods to visualize data from multiple input streams with different latencies from only the same point of time. Sauer *et al.* [17] describe an augmented reality system that synchronizes tracking and video data by hardware triggering. Their software waits for the slowest component before the visualization is updated. For endoscopic surgery, Vogt [115] also uses hardware triggering to synchronize tracking and video data by connecting the S-Video signal (PAL, 50 Hz) of the endoscope system to the synchronization card of the tracking system, which can also be run at 50 Hz.

If virtual and real images do not show a relative lag it means that the images are consistent and there is no error due to a time shift. However there is still the visual offset to haptic senses. Ware *et al.* [116] investigated the effect of latency in a virtual environment with a grasping experiment. They conclude that depending on the size of the object the latency should be ideally as little as 50 ms. Little additions in latencies may cause big decreases of performance. According to their experiment and theory a latency of 175 ms can result in 1200 ms slower grasping than for immediate feedback. This depends on the difficulty of the task. Their experiments showed also a significantly larger percentage of error in their performance with 180 ms latency than with a system that had only 80 ms latency. The experiments of our group [117] confirm these findings for a medical AR system. Therefore an optimal system should feature data synchronization and short latency. We proposed recently an easy and accurate way of measuring the latency in a video see-through system [118].

C. Error Estimation

Tracking in medical AR is mostly fiducial-based because it can guarantee a predictable quality of tracking, which is necessary for the approval of a navigation system.

For an estimation of the overall error calibration, registration and tracking errors have to be computed, propagated, and accumulated. Nicolau and colleagues [44] propose a registration with error prediction for endoscopic augmentation. Fitzpatrick *et al.* [100] compute tracking based errors based on the spatial distribution of marker sets. Hoff *et al.* [18] predict the error for an HMD based navigation system.

An online error estimation is a desirable feature, since physicians have to rely on the visualized data. In current clinical practice, navigation systems stop their visualization in case a factor that decreases the accuracy is known to the system. Instead of stopping the whole system it would be useful to estimate the remaining accuracy and visualize it, so that a surgeon can decide in critical moments, whether to carefully use the data or not. MacIntyre *et al.* [119] suggest in a non-medical setup to predict the error empirically by an adaptive estimator. Our group [120] suggests a way of dynamically estimating the accuracy for optical tracking modeling the physical situation. By integrating the visibility of markers for each camera into the model, a multiple camera setup for reducing the line of sight problem is possible, which ensures a desired level of accuracy. Nafis *et al.* [121] investigate the dynamic accuracy of electromagnetic (EM) tracking. The magnetic field in the tracking volume can be influenced by metallic objects, which can change the measurements significantly. Also the distance of the probe to the field generator and its speed have a strong influence on the accuracy.

Finally it is not enough to estimate the error, but the whole system has to be validated (cf. Jannin *et al.* [122]). Standardized validation procedures have not been used to validate the described systems in order to make the results comparable. The validation of the overall accuracy of an AR system must include the perception of the visualization. In the next section we discuss the effect of misperception in spite of mathematically correct positions in visualizations.

D. Visualization and Depth Perception

The issue of wrong depth perception has been discussed as early as 1992 when Bajura and colleagues [12] described their system. When merging real and virtual images the relative position in depth may not be perceived correctly although all positions are computed correctly. When creating their first setup also

Edwards *et al.* [28] realized that "Experimentation with intra-operative graphics will be a major part of the continuation of the project". Drascic and Milgram [123] provide an overview of perceptual issues in augmented reality system. While many problems of early systems have already been addressed, the issue of a correct depth visualization remains unsolved. Depth cues are physical facts that the human visual system can use in order to refine the spatial model of the environment. These include visual stimuli such as shading but also muscular stimuli such as accommodation and convergence. Psychologists distinguish between a number of different depth cues. Cutting and Vishton review and summarize psychologists' research on nine of the most relevant depth cues [124] revealing the relevance of different depth cues in comparison to each other. They identify interposition as the most important depth cue even though it is only an ordinary qualifier. This means that it can only reveal the order but not a relative or absolute distance. Stereo disparity and motion parallax are the next strongest depth cues in the personal space of up to two meters distance in the named order. The visual system calculates the spatial information together with the depth cues of relative size/density, accommodation, conversion, and areal perspective. Especially the latest one is hardly taken into account for the space under 2 meters unless the subject is in fog or under water.

It is the very nature of AR to provide a view that does not represent the present physical conditions while the visual system expects natural behavior of its environment for correct depth perception. What happens if conflicting depth cues are present? The visual system weights the estimates according to its importance and personal experience [124].

Conflicting cues could result into misperception, adaption, and motion sickness.

1) Misperception: If there are conflicting depth cues it means that at least one depth cue is wrong. Since the visual system is weighting the depth cues together the overall estimate will generally not be correct even though the computer generates geometrically correct images.

Especially optical augmentation provides different parameters for real and virtual images resulting in possibly incompatible depth cues. The effect is described as ghost-like visualization resembling to its unreal and confusing spatial relationship to the real world. The visual system is quite sensitive to relative differences.

Current AR systems handle depth cues well that are based on geometry, as for instance relative size, motion parallax, and stereo disparity. Incorrect visualization of interposition between real and virtual objects has already been identified to be a serious issue by Bajura *et al.* [12]. It has been discussed in more detail by Johnson [125] for augmentation in operating microscopes, Furmanski *et al.* [126] and Livingston *et al.* [127] for an optical see-through, and by our group [117] for video see-through HMDs. The type of AR display makes a difference since relative brightness plays a role in depth perception and optical see-through technology can only overlay brighter virtual images on the real background. Opaque superimposition of virtual objects that are inside a real one is not recommended. Alternatives can be a transparent overlay, wireframes, and a virtual window. Each possibility imposes a trade off: Transparent overlay reduces the contrast of the virtual image, the wireframe is not suitable for complex spatial geometry, and the virtual window locally covers the real view. Lerotic *et al.* [128] suggest to superimpose contours of the real view on the virtual image for better depth perception.

2) Adaption: A wrong visual depth perception can be corrected by learning if another sense can disambiguate the spatial constellation. The sense of proprioception provides exact information about the position of the human body. Biocca and Rolland [129] set up an experiment where the point of view of each subject was repositioned with a video see-through HMD. The adaption time for hand-eye coordination is relatively short and the adaption is successful. Unfortunately, another adaption process is started when the subject is exposed to the normal view again.

3) Motion Sickness: In the worst case conflicting visual cues can cause reduced concentration, headache, nausea etc. These effects have been discussed in the virtual reality and psychology community [130].

Modern theories state that the sickness is not caused by the conflict of cues, but the absence of better information to keep the body upright [131]. Therefore engineers should concentrate on providing more information to the sense of balance (e.g., by making the user sit, unobstructed peripheral view) rather than reducing conflicting visual cues in order to avoid motion sickness. However, motion sickness does not seem to play a big role in AR: In a video see-through HMD based experiment with 20 surgeons we [117] found no indication of the above symptoms even after an average performance time of 16 minutes. In the experiment the subjects were asked to perform a pointing task while standing. The overall lag was reported to be 100 ms for fast rendering visualizations. The remote field of view was not covered. For less immersive AR systems than this one based on an HMD and for systems with similar properties motion sickness is therefore expected to be unlikely.

E. Visualization and Data Representation

3D voxel data cannot be displayed directly with an opaque value for each voxel as for 2D bitmaps. There are three major ways of 3D data representation.

1) Slice Rendering: Slice rendering is the simplest way of rendering. Only a slice of the whole volume is taken for visualization. Radiologists commonly examine CT or MRI data represented by three orthogonal slices intersecting a certain point. The main advantage of this visualization technique is the prevalence of this method in medicine and its simplicity. Another advantage that should not be underestimated is the fact that the visualization defines a plane. Since one degree of freedom is fixed, distances in this plane can be perceived easily. Traub *et al.* [88] showed that slice representations as used in first generation navigation systems have superior capabilities in representing the precise position of a target point. They also found that for finding a target point it can be more efficient to take a different representation of data.

When two or three points of interest and their spatial relationship are supposed to be displayed an oblique slice can be useful. Without a tracked instrument however it is cumbersome to position such a plane.

The major drawback of slice rendering is that this visualization does not show any data off the plane. This is not a constraint for measuring visualizations in plane à la *How far can I go with a drill?* but optimizing questions like *In which direction would a drill be furthest from critical tissue?*

2) Surface Rendering: Surface rendering shows transitions between structures.

Often these transitions are segmented and converted to polygons. The desired tissue is segmented either manually, semi-automatically, or automatically depending on the image source and the desired tissue. The surface polygons of a segmented volume can be calculated by the marching cubes algorithm [132]. Graphic cards offer hardware support for this vertex based 3D data. This includes light effects based on the normals of the surfaces with only little extra computation time.

Recently ray casting techniques became fast enough on graphic cards equipped with a programmable graphics processing unit (GPU) [133]. As the surfaces need not be transformed to polygons the images are smoother. They do not suffer from holes due to discontinuities in the image and the sampling is optimal for a specific viewing direction. Integration of physical phenomena like refraction, reflexion, and shadows are possible with this rendering technique.

As a welcome side effect of surface rendering distances and cutting points can be calculated when visualizing surfaces.

The segmentation step is a major obstacle for this kind of visualization. Segmentation of image data is still considered a hard problem with brisk research going on. Available solutions offer automatic segmentation only for limited number of structures. Manual and semiautomatic solutions can be time-consuming or at least time-consuming to learn. The benefit from such visualization using an interactive segmentation has to justify the extra work load on the team.

3) Volume Rendering: Direct volume rendering [134] creates the visualization by following rays from a certain viewpoint through 3D data. Depending on the source of data and the intended visualization different functions are available for generating a pixel from the ray. The most prominent function is the weighted sum of voxels. A transfer function assigns a color and transparency to each voxel intensity. It may be further refined with the image gradient. A special kind of volume rendering is the digitally reconstructed radiograph (DRR) that provides projections of a CT data set that are similar to X-ray images.

The advantage of direct volume rendering is a visualization that has the capability of emphasizing certain tissues without an explicit segmentation thanks to a certain transfer function. Clear transitions between structures are not necessary. Also cloudy structures and their density can be visualized.

The major disadvantage used to be too slow rendering in particular for AR, but hardware supported rendering algorithms on current graphic cards can provide sufficient frame rates on real 3D data. Currently, 3D texture based [135] and GPU accelerated raycast [133] renderers are the state of the art in terms of speed and image quality, where the latter offer better image quality. Also the ray casting technique needs clear structures in the image for acceptable results, which can be realized with contrast agents or segmentation.

F. User Interaction in Medical AR Environments

Classic 2D computer interaction paradigms such as windows, mouse pointer, menus, and keyboards do not translate well for 3D displays in common. Bowman [87] gives a comprehensive introduction into 3D user interfaces and detailed information why 3D interaction is difficult. The book gives general advice for creating new user interfaces. Reitinger *et al.* [136] suggest a 3D user interface for liver planning. Even though the suggested planning is done in pure virtual space the ideas apply to AR as well. They use tracked instruments and a tracked glass plane for defining points and planes in a tangible way. They combine tangible 3D interaction and classic 2D user interfaces in an effective way.

Navab *et al.* [137] suggest a new paradigm for interaction with 3D data. A virtual mirror is augmented into the scene. The physician has the possibility to explore the data from any side using the mirror without giving up the registered view. Since the interaction uses a metaphor that has a very similar real counterpart, no extra learning is expected for a user.

Apart from 2D/3D issues, standard 2D computer interfaces such as mice are not suited for the OR because of sterility and ergonomic reasons. Fortunately, medical systems are highly specialized on the therapy. Since a specialized application has a limited number of meaningful visualization modes the user interface can be highly specialized as well. Context aware systems can further reduce the degree of interaction. Automatic workflow recovery as suggested by Ahmadi *et al.* [138] could detect phases of the surgery and with this information the computer system could offer suitable information for each phase.

V. Perspective

After two decades of research on medical AR the basic concepts seem to be well understood and the enabling technologies are now enough advanced to meet the basic requirements for a number of medical applications. We are encouraged by our clinical partners to believe that medical AR systems and solutions could be accepted by physicians, if they are integrated seamlessly into the clinical workflow and if they provide a significant benefit at least for one particular phase of this workflow. A perfect medical AR user interface would be integrated in such a way that the user would not feel its existence, while taking full advantage of additional *in situ* information it provides.

Generally, augmented optics and augmented endoscopes do not dramatically change the OR environment, apart from adding a tracking system imposing free line of sight constraints, and change the current workflow minimally and smoothly. The major issue they are facing is appropriate depth perception within a mixed environment, which is subject of active research within the AR community [128], [137], [139], [140]. Augmented medical imaging devices provide aligned views by construction and do not need additional tracking systems. If they do not restrict the working space of the physicians these systems have the advantage of a smooth integration into the medical workflow. In particular, the CAMC system is currently getting deployed within three German hospitals and will be soon tested on 40 patients in each of these medical centers.

The AR window and video-see-through HMD systems still need hardware and software improvement in order to satisfy the requirements of operating physicians. In both cases, the community also needs new concepts and paradigms allowing the physicians to take full advantage of the augmented virtual data, to easily and intuitively interact with it, and to experience this dynamic mixed environment as one unique and correctly perceived 3D world. We share the expectations of business analysts [141] that the hype level of augmented reality will reach its maximum in a few years and that medical AR will be one of its first killer applications, saving lives of many future patients.

REFERENCES

[1] H. Steinhaus, "Sur la localisation au moyen des rayons x," *Comptes Rendus de L'Acad. des Sci.*, vol. 206, pp. 1473–1475, 1938.

[2] I. Sutherland, "A head-mounted three dimensional display," in *Proc. Fall Joint Computer Conf.*, 1968, pp. 757–764.

[3] D. Roberts, J. Strohbehn, J. Hatch, W. Murray, and H. Kettenberger, "A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope," *J. Neurosurg.*, vol. 65, no. 4, pp. 545–549, 1986.

[4] T. Caudell and D. Mizell, "Augmented reality: An application of heads-up display technology to manual manufacturing technology augmented reality," in *Proc. Hawaii Int. Conf. on Syst. Sci.*, 1992.

[5] W. Mackay, G. Velay, K. Carter, C. Ma, and D. Pagani, "Augmenting reality: Adding computational dimensions to paper," *Commun. ACM*, vol. 36, no. 7, pp. 96–97, 1993.

[6] S. Feiner, B. Macintyre, and D. Seligmann, "Knowledge-based augmented reality," *Commun. ACM*, vol. 36, no. 7, pp. 53–62, 1993.

[7] P. Wellner, W. Mackay, and R. Gold, "Computer augmented environments: Back to the real world," *Commun. ACM*, vol. 36, no. 7, pp. 24–26, 1993.

[8] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Trans. Inf. Syst.*, pp. 1321–1329, 1994.

[9] R. T. Azuma, "A survey of augmented reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997.

[10] R. T. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, "Recent advances in augmented reality," *IEEE Comput. Graphics Appl.*, vol. 21, pp. 34–47, 2001.

[11] F. P. Brooks, "The computer scientist as toolsmith ii," *Commun. ACM*, vol. 39, no. 3, pp. 61–68, 1996.

[12] M. Bajura, H. Fuchs, and R. Ohbuchi, "Merging virtual objects with the real world: Seeing ultrasound imagery within the patient," in *Proc. 19th Annu. Conf. on Computer Graphics and Interactive Techniques*, 1992, pp. 203–210.

[13] M. Bajura and U. Neumann, "Dynamic registration correction in video-based augmented reality systems," *IEEE Comput. Graph. Appl.*, vol. 15, no. 5, pp. 52–60, 1995.

[14] M. C. Jacobs, M. A. Livingston, and A. State, "Managing latencyin complex augmented reality systems," in *Proc. ACM 1997 Symp. on Interactive 3D Graphics*, 1997, pp. 49–54.

[15] A. State, M. A. Livingston, W. F. Garrett, G. Hirota, M. C. Whitton, E. D. Pisano, and H. Fuchs, "Technologies for augmented reality systems: Realizing ultrasound-guided needle biopsies," in *SIGGRAPH'96: Proc. 23rd Annu. Conf. on Computer Graphics and Interactive Techniques*, New York, NY, USA, 1996, pp. 439–446.

[16] M. Rosenthal, A. State, J. Lee, G. Hirota, J. Ackerman, E. D. P. K. Keller, M. Jiroutek, K. Muller, and H. Fuchs, "Augmented reality guidance for needle biopsies: An initial randomized, controlled trial in phantoms," *Medical Image Anal.*, vol. 6, no. 3, pp. 313–320, 2002.

[17] F. Sauer, F. Wenzel, S. Vogt, Y. Tao, Y. Genc, and A. Bani-Hashemi, "Augmented workspace: Designing an AR testbed," in *Proc. IEEE and ACM Int. Symp. on Augmented Reality*, 2000, pp. 47–53.

[18] W. A. Hoff and T. L. Vincent, "Analysis of head pose accuracy in augmented reality," *IEEE Trans. Visualiz. Computer Graphics*, vol. 6, 2000.

[19] D. L. Wright, J. P. Rolland, and A. R. Kancherla, "Using virtual reality to teach radiographic positioning," *Radiologic Int. Technol.*, vol. 66, no. 4, pp. 233–238, 1995.

[20] Y. Argotti, L. Davis, V. Outters, and J. Rolland, "Dynamic superimposition of synthetic objects on rigid and simple-deformable real objects," *Computers & Graphics*, vol. 26, no. 6, pp. 919–930, 2002.

[21] T. Sielhorst, T. Blum, and N. Navab, "Synchronizing 3d movements for quantitative comparison and simultaneous visualization of actions," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2005.

[22] G. Luo and E. Peli, "Use of an augmented-vision device for visual search by patients with tunnel vision," *Investigative Ophthalmology & Visual Science*, vol. 47, no. 9, pp. 4152–4159, 2006.

[23] J. P. Rolland and H. Fuchs, "Optical versus video see-through head-mounted displays in medical visualization," *Presence*, vol. 9, pp. 287–309, 2000.

[24] O. Cakmakci and J. Rolland, "Head-worn displays: A review," *Int. J. Display Int. Technol.*, vol. 2, pp. 199–216, Sept. 2006.

[25] P. J. Kelly, G. Alker, and S. Goerss, "Computer-assisted stereotactic laser microsurgery for the treatment of intracranial neoplasms," *Neurosurgery*, vol. 10, pp. 324–331, 1982.

[26] J. Hatch and J. S. D. W. Roberts, "Reference-display system for the integration of CT scanning and the operating microscope," in *Proc. 11th Annu. Northeast Bioeng. Conf.*, 1985.

[27] E. M. Friets, J. W. Strohbehn, J. F. Hatch, and D. W. Roberts, "A frameless stereotaxic operating microscope for neurosurgery," *IEEE Trans. Biomed. Eng.*, vol. 36, no. 6, Jun. 1989.

[28] P. J. Edwards, D. D. Hill, D. D. Hawkes, and D. A. Colchester, "Neurosurgical guidance using the stereo microscope," in *Proc. First Int. Conf. Computer Vision, Virtual Reality and Robotics in Medicine (CVRMed'95)*, 1995.

[29] A. P. King, P. J. Edwards, C. R. Maurer, Jr., D. A. de Cunha, D. J. Hawkes, D. L. G. Hill, R. P. Gaston, M. R. Fenlon, A. J. Strong, C. L. Chandler, A. Richards, and M. J. Gleeson, "Design and evaluation of a system for microscope-assisted guided interventions," *IEEE Trans. Med. Imag.*, vol. 19, no. 11, pp. 1082–1093, Nov. 2000.

[30] J. Berger and D. Shin, "Computer-vision-enabled augmented reality fundus biomicroscopy," *Ophthalmology*, vol. 106, no. 10, pp. 1935–1941, 1999.

[31] W. Birkfellner, M. Figl, K. Huber, F. Watzinger, F. Wanschitz, J. Hummel, R. Hanel, W. Greimel, P. Homolka, R. Ewers, and H. Bergmann, "A head-mounted operating binocular for augmented reality visualization in medicine—Design and initial evaluation," *IEEE Trans. Med. Imag.*, vol. 21, no. 8, pp. 991–997, Aug. 2002.

[32] W. Birkfellner, K. Huber, F. Watzinger, M. Figl, F. Wanschitz, R. Hanel, D. Rafolt, R. Ewers, and H. Bergmann, "Development of the varioscopear—A see-through hmd for computer-aided surgery," in *Proc. IEEE and ACM Int. Symp. on Augmented Reality*, 2000, pp. 54–59.

[33] M. Figl, C. Ede, J. Hummel, F. Wanschitz, R. Ewers, H. Bergmann, and W. Birkfellner, "A fully automated calibration method for an optical see-through head-mounted operating microscope with variable zoom and focus," *IEEE Trans. Med. Imag.*, vol. 24, no. 11, pp. 1492–1499, Nov. 2005.

[34] R. Holloway, "Registration error analysis for augmented reality," *Presence: Teleoperators and Virtual Env.*, vol. 6, no. 4, pp. 413–432, 1997.

[35] Y. Masutani, M. Iwahara, O. Samuta, Y. Nishi, N. Suzuki, M. Suzuki, T. Dohi, H. Iseki, and K. Takakura, "Development of integral photography-based enhanced reality visualization system for surgical support," *Proc. lSCAS*, vol. 95, pp. 16–17, 1995.

[36] H. Liao, S. Nakajima, M. Iwahara, E. Kobayashi, I. Sakuma, N. Yahagi, and T. Dohi, "Intra-operative real-time 3-D information display system based on integral videography," in *Proc. Int. Conf. Med. Image Computing and Computer Assisted Intervention (MICCAI)*, 2001, pp. 392–400.

[37] H. Liao, N. Hata, S. Nakajima, M. Iwahara, I. Sakuma, and T. Dohi, "Surgical navigation by autostereoscopic image overlay of integral videography," *IEEE Trans. Int. Technol. Biomed.*, vol. 8, no. 2, pp. 114–121, 2004.

[38] M. Blackwell, C. Nikou, A. M. D. Gioia, and T. Kanade, I. W. M. Wells, A. C. F. Colchester, and S. L. Delp, Eds., "An image overlay system for medical data visualization," in *Proc. First Int. Conf. of Medical Image Computing and Computer-Assisted Intervention (MICCAI) Lecture Notes in Comput. Sci.*, Cambridge, MA, Oct. 1998, vol. 1496, pp. 232–240.

[39] G. Goebbels, K. Troche, M. Braun, A. Ivanovic, A. Grab, K. von Lübtow, R. Sader, F. Zeilhofer, K. Albrecht, and K. Praxmarer, "Arsystricorder—development of an augmented reality system for intraoperative navigation in maxillofacial surgery," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2003.

[40] S. Wesarg, E. Firle, B. Schwald, H. Seibert, P. Zogal, and S. Roeddiger, R. L. Galloway, Jr., Ed., "Accuracy of needle implantation in brachytherapy using a medical AR system: A phantom study," *Proc. 2004 SPIE Medical Imaging: Visualization, Image-Guided Procedures, and Display*, vol. 5367, pp. 341–352, 2004.

[41] W. Lorensen, H. Cline, C. Nafis, R. Kikinis, D. Altobelli, L. Gleason, G. Co, and N. Schenectady, "Enhancing reality in the operating room," in *IEEE Conf. on Visualization*, 1993, pp. 410–415.

[42] W. E. L. Grimson, T. Lozano-Perez, W. M. Wells III, G. J. Ettinger, S. J. White, and R. Kikinis, "An automatic registration method for frameless stereotaxy, image guided surgery, and enhanced reality visualization," *IEEE Trans. Med. Imag.*, vol. 15, no. 2, pp. 129–140, Apr. 1996.

[43] Y. Sato, M. Nakamoto, Y. Tamaki, T. Sasama, I. Sakita, Y. Nakajima, M. Monden, and S. Tamura, "Image guidance of breast cancer surgery using 3-d ultrasound images and augmented reality visualization," *IEEE Trans. Med. Imag.*, vol. 17, no. 5, Oct. 1998.

[44] S. Nicolau, X. Pennec, L. Soler, and N. Ayache, "An accuracy certified augmented reality system for therapy guidance," in *Proc. 8th Eur. Conf. on Computer Vision (ECCV 04)*, Prague, May 2004, vol. 3023, pp. 79–91, Lecture Notes in Computer Science.

[45] W. Lau, "History of endoscopic and laparoscopic surgery," *World Int. J.f Surgery*, vol. 21, no. 4, pp. 444–453, 1997.

[46] G. Litynski, "Endoscopic surgery: The history, the pioneers," *World Int. J. Surgery*, vol. 23, no. 8, pp. 745–753, 1999.

[47] G. Berci and K. A. Forde, "History of endoscopy—What lessons have we learned from the past?," *Surgical Endoscopy*, vol. 14, pp. 5–15, 2002.

[48] W. Freysinger, A. Gunkel, and W. Thumfart, "Image-guided endoscopicent surgery," *Eur. Archives of Otorhinolaryngology*, vol. 254, no. 7, pp. 343–346, 1997.

[49] R. Shahidi, B. Wang, M. Epitaux, R. Grzeszczuk, and J. Adler, I. W. M. Wells, A. C. F. Colchester, and S. L. Delp, Eds., "Volumetric image guidance via a stereotactic endoscope," in *Proc. First Int. Conf. Med. Image Computing and Computer-Assisted Intervention (MICCAI)*, Cambridge, MA, Oct. 1998, vol. 1496, pp. 241–252, Lecture Notes in Computer Science.

[50] M. Scholz, W. Konen, S. Tombrock, B. Fricke, and L. Adams, "Development of an endoscopic navigation system based on digitalimage processing," *Computer Aided Surgery*, vol. 3, pp. 134–143, 1998.

[51] F. Mourgues and È. Coste-Manière, "Flexible calibration of actuated stereoscopic endoscope for overlay in robot assisted surgery," in *Proc. Int. Conf. Med. Image Computing and Computer Assisted Intervention (MICCAI)*, 2002, pp. 25–34.

[52] R. Khadem, M. R. Bax, J. A. Johnson, E. P. Wilkinson, and R. Shahidi, "Endoscope calibration and accuracy testing for 3d/2d image registration," in *Proc. Int. Conf. Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, 2001, pp. 1361–1362.

[53] W. E. Smith, N. Vakil, and S. A. Maislin, "Correction of distortion in endoscope images," *IEEE Trans. Med. Imag.*, vol. 11, no. 1, pp. 117–122, Feb. 1992.

[54] S. De Buck, J. Van Cleynenbreuge, I. Geys, T. Koninckx, P. R. Koninck, and P. Suetens, "A system to support laparoscopic surgery by augmented reality visualization," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2001, pp. 691–698.

[55] R. Shahidi, M. R. Bax, C. R. Maurer, Jr., J. A. Johnson, E. P. Wilkinson, B. Wang, J. B. West, M. J. Citardi, K. H. Manwaring, and R. Khadem, "Implementation, calibration and accuracy testing of an image-enhanced endoscopy system," *IEEE Trans. Med. Imag.*, vol. 21, no. 12, pp. 1524–1535, 2002.

[56] J. Heikkilä and O. Silvén, "A four-step camera calibration procedure with implicit image correction," in *Proc. IEEE Conf. Computer Vision and Pattern Recognition (CVPR)*, 1997, pp. 1106–1112.

[57] R. Tsai, "A versatile camera calibration technique for high accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses," *IEEE Int. J. Robot. Autom.*, vol. RA-3, no. 4, pp. 323–344, 1987.

[58] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Trans. .Pattern Anal. Mach. Intell.*, vol. 22, pp. 1330–1334, Nov. 2000.

[59] D. Stoyanov, A. Darzi, and G. Z. Yang, "Laparoscope self-calibration for robotic assisted minimally invasive surgery," in *Proc. Int. Conf. Med. Image Computing and Computer Assisted Intervention (MICCAI)*, J. Duncan and G. Gerig, Eds., 2005, vol. 3750, pp. 114–121, Lecture Notes in Computer Science.

[60] R. Willson, "Modeling and calibration of automated zoom lenses.," Ph.D. dissertation, Robotics Inst., Carnegie Mellon Univ., Pittsburgh, PA, Jan. 1994.

[61] G. Bianchi, C. Wengert, M. Harders, P. Cattin, and G. Székely, "Camera-marker alignment framework and comparison with hand-eye calibration for augmented reality applications 2005," *ISMAR*, pp. 188–189, Oct. 2005.

[62] S. Nicolau, L. Goffin, and L. Soler, "A low cost and accurate guidance system for laparoscopic surgery: Validation on an abdominal phantom," in *ACM Symp. on Virtual Reality Software and Int. Technol.*, Nov. 2005, pp. 124–133.

[63] M. Scheuering, A. Schenk, A. Schneider, B. Preim, and G. Greiner, "Intraoperative augmented reality for minimally invasive liver interventions," *Proc. 2003 SPIE Medical Imag.: Visualization, Image-Guided Procedures, and Display,*, 2003.

[64] J. Schmidt, F. Vogt, and H. Niemann, "Robust hand-eye calibration of an endoscopic surgery robot using dual quaternions," in *25th DAGM Symp. Pattern Recogn.*, B. Michaelis and G. Krell, Eds., 2003, vol. 2781, pp. 548–556, Lecture Notes in Computer Science.

[65] G. Marti, V. Bettschart, J.-S. Billiard, and C. Baur, "Hybrid method forboth calibration and registration of an endoscope with an active optical tracker," *Comput. Assisted Radiology and Surgery*, 2004.

[66] T. Yamaguchi, M. Nakamoto, Y. Sato, K. Konishi, M. Hashizume, N. Sugano, H. Yoshikawa, and S. Tamura, "Development of a camera model and calibration procedure for oblique-viewing endoscopes," *Computer Aided Surgery*, vol. 9, no. 5, pp. 203–214, 2004.

[67] S. De Buck, F. Maes, A. D'Hoore, and P. Suetens, N. Ayache, S. Ourselin, and A. Maeder, Eds., "Evaluation of a novel calibration technique for optically tracked oblique laparoscopes," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, Brisbane, Australia, Oct./Nov. 2007, vol. 4791, pp. 467–474, Lecture Notes in Computer Science.

[68] I. Bricault, G. Ferretti, and P. Cinquin, "Registration of real and CT-derived virtual bronchoscopic images to assist transbronchial biopsy," *IEEE Trans. Med. Imag.*, vol. 17, no. 5, pp. 703–714, 1998.

[69] K. Mori, D. Deguchi, J. Ichi Hasegawa, Y. Suenaga, J. ichiro Toriwaki, H. Takabatake, and H. Natori, "A method for tracking the camera motion of real endoscope by epipolar geometry analysis and virtual endoscopy system," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2001, vol. 2208, pp. 1–8, Lecture Notes in Computer Science.

[70] K. Mori, D. Deguchi, K. Akiyama, T. Kitasaka, C. R. Maurer Jr., Y. Suenaga, H. Takabatake, M. Mori, and H. Natori, "Hybrid bronchoscope tracking using a magnetic tracking sensor and image registration," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2005, pp. 543–550.

[71] I. Wegner, M. Vetter, M. Schoebinger, I. Wolf, and H. Meinzer, K. R. Cleary and R. L. Galloway Jr., Eds., "Development of a navigation system for endoluminal brachytherapy in human lungs," in *Proc. SPIE Medical Imaging 2006: Visualization, Image-Guided Procedures, and Display*, Mar. 2006, vol. 6141, pp. 23–30.

[72] T. Klein, J. Traub, H. Hautmann, A. Ahmadian, and N. Navab, "Fiducial free registration procedure for navigated bronchoscopy," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2007.

[73] S. Krüger, F. Vogt, W. Hohenberger, D. Paulus, H. Niemann, and C. H. Schick, "Evaluation of computer-assisted image enhancementin minimal invasive endoscopic surgery," *Methods Inf. Med.*, vol. 43, no. 4, pp. 362–366, 2004.

[74] H. Fuchs, M. A. Livingston, R. Raskar, D. Colucci, K. Keller, A. State, J. R. Crawford, P. Rademacher, S. H. Drake, and A. A. Meyer, I. W. M. Wells, A. C. F. Colchester, and S. L. Delp, Eds., "Augmented reality visualization for laparoscopic surgery," in *Proc. First Int. Conf. of Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, Cambridge, MA, Oct. 1998, vol. 1496, pp. 934–943, Lecture Notes in Computer Science.

[75] D. Dey, D. Gobbi, P. Slomka, K. Surry, and T. Peters, "Automatic fusion of freehand endoscopic brain images to three-dimensional surfaces: Creating stereoscopic panoramas," *IEEE Trans. Med. Imag.*, vol. 21, no. 1, pp. 23–30, Jan. 2002.

[76] T. Kawamata, H. Iseki, T. Shibasaki, and T. Hori, "Endoscopic augmented reality navigation system for endonasal transsphenoidal surgery to treat pituitary tumors: Technical note," *Neurosurgery*, vol. 50, no. 6, pp. 1393–1397, 2002.

[77] J. Ellsmere, J. Stoll, D. W. Rattner, D. Brooks, R. Kane, W. M. Wells III, R. Kikinis, and K. Vosburgh, R. E. Ellis and T. M. Peters, Eds., "A navigation system for augmenting laparoscopic ultrasound," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2003, pp. 184–191, Lecture Notes in Computer Science.

[78] N. Navab, M. Mitschke, and A. Bani-Hashemi, "Merging visible and invisible: Two camera-augmented mobile C-arm (CAMC) applications," in *Proc. IEEE and ACM Int. Workshop on Augmented Reality*, San Francisco, CA, 1999, pp. 134–141.

[79] G. Fichtinger, A. Deguet, K. Masamune, E. Balogh, G. S. Fischer, H. Mathieu, R. H. Taylor, S. J. Zinreich, and L. M. Fayad, "Image overlay guidance for needle insertion in ct scanner," *IEEE Trans. Biomed. Engi.*, vol. 52, no. 8, pp. 1415–1424, Aug. 2005.

[80] K. Masamune, Y. Masutani, S. Nakajima, I. Sakuma, T. Dohi, H. Iseki, and K. Takakura, "Three-dimensional slice image overlay system with accurate depth perception for surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, Oct. 2000, vol. 1935, pp. 395–402, Lecture Notes in Computer Science.

[81] G. Fischer, A. Deguet, D. Schlattman, L. Fayad, S. Zinreich, R. Taylor, and G. Fichtinger, "Image overlay guidance for mri arthrography needle insertion," *Computer Aided Surgery*, vol. 12, no. 1, pp. 2–4, 2007.

[82] G. D. Stetten and V. S. Chib, "Overlaying ultrasound images on direct vision," *Int. J. Ultrasound in Medicine*, vol. 20, pp. 235–240, 2001.

[83] G. Stetten, V. Chib, and R. Tamburo, "Tomographic reflection to merge ultrasound images with direct vision," in *IEEE Proc. Applied Imagery Pattern Recognition (AIPR) Annu. Workshop*, 2000, pp. 200–205.

[84] N. Glossop and Z. Wang, R. E. Ellis and T. M. Peters, Eds., "Laser projection augmented reality system for computer assisted surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2003, vol. 2879, pp. 239–246, Lecture Notes in Computer Science.

[85] T. Sasama *et al.*, "A novel laser guidance system for alignment of linear surgical tools: Its principles and performance evaluation as a man-machine system," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, London, U.K., 2002, pp. 125–132.

[86] T. Wendler, J. Traub, S. Ziegler, and N. Navab, R. Larsen, M. Nielsen, and J. Sporring, Eds., "Navigated threedimensional beta probe for optimal cancer resection," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI) vol. 4190 of Lecture Notes in Computer Science*, Copenhagen, Denmark, Oct. 2006, pp. 561–569.

[87] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev, *3D User-Interfaces: Theory and Practice*. Redwood City, CA, USA: Addison Wesley Longman Publishing Co., Inc., 2004.

[88] J. Traub, P. Stefan, S.-M. Heining, T. Sielhorst, C. Riquarts, E. Eu-ler, and N. Navab, R. Larsen, M. Nielsen, and J. Sporring, Eds., "Hybrid navigation interface for orthopedic and trauma surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, Copenhagen, Denmark, Oct. 2006, vol. 4190, pp. 373–380, Lecture Notes in Computer Science.

[89] T. Peters, C. Henri, P. Munger, A. Takahashi, A. Evans, B. Davey, and A. Olivier, "Integration of stereoscopic DSA and 3D MRI for image-guided neurosurgery," *Comput Med Imaging Graph.*, vol. 18, no. 4, pp. 289–299, 1994.

[90] C. Calvano, M. Moran, L. Tackett, P. Reddy, K. Boyle, and M. Pankra-tov, "New visualization techniques for in utero surgery: Amnioscopy with a three-dimensional head-mounted display and a computer-controlled endoscope.," *J. Endourol.*, vol. 12, no. 5, pp. 407–410, 1998.

[91] G. Hanna, S. Shimi, and A. Cuschieri, "Task performance in endoscopic surgery is influenced by location of the image display," *Ann. Surg.*, vol. 227, no. 4, pp. 481–484, 1998.

[92] J. B. A. Maintz and M. A. Viergever, "A survey of medical image registration," *Medical Image Analysis*, vol. 2, pp. 1–36, Mar. 1998.

[93] M. Tuceryan, D. S. Greer, R. T. Whitaker, D. E. Breen, C. Crampton, E. Rose, and K. H. Ahlers, "Calibration requirements and proceduresfor a monitor-based augmented reality system," *IEEE Trans. Visualiz. Computer Graphics*, vol. 1, pp. 255–273, Sept. 1995.

[94] C. R. Maurer Jr., J. M. Fitzpatrick, M. Y. Wang, J. Robert, L. Galloway, R. J. Maciunas, and G. S. Allen, "Registration of head volume images using implantable fiducial markers," *IEEE Trans. Med. Imag.*, vol. 16, no. 4, pp. 447–462, Aug. 1997.

[95] J. D. Stefansic, A. J. Herline, Y. Shyr, W. C. Chapman, J. M. Fitzpatrick, and R. L. Galloway, "Registration of physical space to laparoscopic image space for use in minimally invasive hepatic surgery," *IEEE Trans. Medical Imaging*, vol. 19, no. 10, pp. 1012–1023, Oct. 2000.

[96] M. Feuerstein, S. M. Wildhirt, R. Bauernschmitt, and N. Navab, J. S. Duncan and G. Gerig, Eds., "Automatic patient registration for port placement in minimally invasive endoscopic surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, Palm Springs, CA, Sept. 2005, vol. 3750, pp. 287–294, Lecture Notes in Computer Science.

[97] M. Feuerstein, T. Mussack, S. M. Heining, and N. Navab, "Intra-operative laparoscope augmentation for port placement and resection planning in minimally invasive liver resection," *IEEE Trans. Med. Imag.*, vol. 27, pp. 355–369, Mar. 2008.

[98] M. Baumhauer, T. Simpfendörfer, R. Schwarz, M. Seitel, B. Müller-Stich, C. Gutt, J. Rassweiler, H.-P. Meinzer, and I. Wolf, K. R. Cleary and M. I. Miga, Eds., "Soft tissue navigation for laparoscopic prostatectomy: Evaluation of camera pose estimation for enhanced visualization," in *Proc. SPIE Medical Imaging 2007: Visualization and Image-Guided Procedures*, San Diego, CA, Feb. 2007.

[99] R. U. Thoranaghatte, G. Zheng, F. Langlotz, and L.-P. Nolte, "Endoscope-based hybrid navigation system for minimally invasive ventral spine surgeries," *Computer Aided Surgery*, vol. 10, pp. 351–356, Sept./Nov. 2005.

[100] J. M. Fitzpatrick, J. B. West, and C. R. Maurer Jr., "Predicting error in rigid-body point-based registration," *IEEE Trans. Med. Imag.*, vol. 14, no. 5, pp. 694–702, Oct. 1998.

[101] R. Grzeszczuk, S. Chin, R. Fahrig, H. Abassi, H. Holz, J. A. Daniel Kiml, and R. Shahidi, "A fluoroscopic x-ray registration processfor three-dimensional surgical navigation," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, Lecture Notes in Computer Science, 2000, Springer-Verlag.

[102] M. J. Murphy, "An automatic six-degree-of-freedom image registration algorithm for image-guided frameless stereotaxic radiosurgery," *Medical Phys.*, vol. 24, no. 6, pp. 857–866, 1997.

[103] M. Feuerstein, T. Mussack, S. M. Heining, and N. Navab, K. R. Cleary and M. I. Miga, Eds., "Registration-free laparoscope augmentation for intra-operative liver resection planning," in *Medical Imaging 2007: Visualization and Image-Guided Procedures, Proc. SPIE*, San Diego, CA, Feb. 2007.

[104] P. A. Grützner, A. Hebecker, H. Waelti, B. Vock, L.-P. Nolte, and A. Wentzensen, "Clinical sludy for registration-free 3d-navigation with the siremobil iso-c^{3D} mobile C-arm," *Electromedica*, vol. 71, no. 1, pp. 7–16, 2003.

[105] D. Burschka, M. Li, R. Taylor, and G. D. Hager, "Scale-invarianlregistration of monocular endoscopic images to ct-scans for sinus surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, C. Barillol, D. Haynor, and P. Hellier, Eds., 2004, vol. 3217, pp. 413–421, Lecture Notes in Computer Science.

[106] C. Wengert, P. Cattin, J. M. Duff, C. Baur, and G. Székely, "Markerless endoscopic registration and referencing," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, R. Larsen, M. Nielsen, and J. Sporring, Eds., 2006, Lecture Notes in Computer Science.

[107] C. Maurer, Jr., "Investigation of intraopera live brain deformation using a 1.5-T interventional MR system: Preliminary results," *IEEE Trans. Med. Imag.*, vol. 17, no. 5, p. 817, Oct. 1998.

[108] M. Nakamoto, Y. Sato, M. Miyamoto, Y. Nakamjima, K. Konishi, M. Shimada, M. Hashizume, and S. Tamura, "3d ultrasound system using a magneto-optic hybrid tracker for augmented reality visualization in laparoscopic liver surgery," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, T. Dohiand and R. Kikinis, Eds., 2002, vol. 2489, pp. 148–155, Lecture Notes in Computer Science.

[109] J. Leven, D. Burschka, R. Kumar, G. Zhang, S. Blumenkranz, X. D. Dai, M. Awad, G. D. Hager, M. Marohn, M. Choli, C. Hasser, and R. H. Taylor, "Davinci canvas: A teterobotic surgical system wilh integrated, robot-assisted, laparoscopic ultrasound capability," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI), Vol. 3749 of Lecture Notes in Computer Science*, Sept. 2005, pp. 811–818, Springer-Verlag.

[110] M. Feuerstein, T. Reichl, J. Vogel, A. Schneider, H. Feussner, and N. Navab, "Magneto-optic tracking of a flexible laparoscopic ultrasound transducer for laparoscope augmentation," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, N. Ayache, S. Ourselin, and A. Maeder, Eds., Brisbane, Australia, Oct./Nov. 2007, vol. 4791, pp. 458–466, Lecture Notes in Computer Science.

[111] F. S. Azar, D. N. Metaxas, and M. D. Schnall, "Methods for modeling and predicting mechanical deformations of the breast under external perturbations," *Medical Image Analysis*, vol. 6, no. 1, pp. 1–27, 2002.

[112] J. W. Wong, M. B. Sharpe, D. A. Jaffray, V. R. Kini, J. M. Robertson, J. S. Stromberg, and A. A. Martinez, "The use of active breathing control (abc) to reduce margin for breathing motion," *Int. Int. J. Radiation Oncology*Biology*Phys.*, vol. 44, pp. 911–919, July 1999.

[113] J. M. Bailer, L. A. Dawson, S. Kazanjian, C. McGinn, K. K. Brock, T. Lawrence, and R. T. Haken, "Determination of ventilatory liver movement via radiographic evaluation of diaphragm position," *Int.. J. Radiation Oncology*Biology*Phys.*, vol. 51, pp. 267–270, Sept. 2001.

[114] M. Baumhauer, M. Feuerstein, H.-P. Meinzer, and J. Rassweiler, "Navigation in endoscopic soft tissue surgery: Perspectives and limitations," *Int. J. Endourology*, vol. 22, pp. 1–16, Apr. 2008.

[115] F. Vogl, "Augmented light field visualization and real-time image enhancement for computer assisted endoscopic surgery," Ph.D. dissertation, Universilal Erlangen-Nürnberg, , 2005.

[116] C. Ware and R. Balakrishnan, "Reaching for objects in VR displays: Lag and frame rate," *ACM Trans. Computer-Human Interaction*, vol. 1, no. 4, pp. 331–356, 1994.

[117] T. Sielhorst, C. Bichlmeier, S. M. Heining, and N. Navab, "Depth perception a major issue in medical ar: Evaluation study by twenty surgeons," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, R. Larsen, M. Nielsen, and J. Sporring, Eds., 2006, Lecture Notes in Computer Science.
[118] T. Sielhorst, W. Sa, A. Khamene, F. Sauer, and N. Navab, "Measurement of absolute latency for video see through augmented reality," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2007.
[119] B. Mactntyre, E. M. Coelho, and S. Julier, "Estimating and adapting to registration errors in augmented reality systems," in *Proc. IEEE Virtual Reality (VR)*, 2002.
[120] T. Sielhorst, M. A. Bauer, O. Wenisch, G. Klinker, and N. Navab, "Online estimation of the target registration error for n-ocular optical-tracking systems," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2007, To appear at.
[121] C. Nafis, V. Jensen, L. Beauregard, and P. Anderson, "Method for estimating dynamic em tracking accuracy of surgical navigation tools," in *Proc. SPIE Medical Imaging 2006: Visualization, Image Guided Procedures, and Display*, K. R. Cleary and R. L. Galloway, Jr., Eds., Mar. 2006, vol. 6141.
[122] P. Jannin, J. Fitzpatrick, D. Hawkes, X. Pennec, R. Shahidi, and M. Vannier, "Validation of medical image processing in image-guided therapy," *IEEE Trans. Med. Imag.*, vol. 21, no. 12, pp. 1445–1449, Dec. 2002.
[123] D. Drascic and P. Milgram, "Perceptual issues in augmented reality," *SPIE Volume 2653: Stereoscopic Displays and Virtual Reality Syst.*, vol. 2653, pp. 123–134, 1996.
[124] J. E. Cutting and P. M. Vishton, W. Epstein and S. Rogers, Eds., "Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth," *Perception of Space and Motion*, pp. 69–117, 1995.
[125] L. G. Johnson, P. Edwards, and D. Hawkes, "Surface transparency makes stereo overlays unpredictable: The implications for augmented reality," in *Medicine Meets Virtual Reality (MMVR), Vol. 94 of Studies in Health Int. Technol. and Inf.*, J. D. Westwood, Ed. : IOS Press, 2002, pp. 131–136.
[126] C. Furmanski, R. Azuma, and M. Daily, "Augmented-reality visualizations guided by cognition: Perceptual heuristics for combining visible and obscured information," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2002.
[127] M. Livingston, I. JE, H. JL, H. TH, and S. D. Julier, "Resolving multiple occluded layers in augmented reality," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2003, pp. 56–65.
[128] M. Lerotic, A. J. Chung, G. Mylonas, and G.-Z. Yang, "pq-space based non-photorealistic rendering for augmented reality," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2007, pp. 102–109.
[129] F. A. Biocca and J. P. Rolland, "Virtual eyes can rearrange your body: Adaptation to visual displacement in see-through, head-mounted displays," *Presence: Teleoperators and Virtual Env.*, vol. 7, pp. 262–277, 1998.
[130] E. M. Kolasinski, S. L. Goldberg, and J. H. Hiller, Simulator sickness in virtual environments U.S. Army Research Institute—Simulator Syst. Research Unit, Technical Report 1027, 1995.
[131] G. Riccio, "An ecological theory of motion and postural instability," *Ecological Psychology*, vol. 3, no. 3, pp. 195–240, 1991.
[132] W. E. Lorensen and H. E. Cline, "Marching cubes: A high resolution 3d surface construction algorithm," in *Proc. 14th Annu. Conf. on SIGGRAPH'87: Computer Graphics and Interactive Techniques*, New York, NY, 1987, pp. 163–169.
[133] J. Krüger and R. Westermann, "Acceleration techniques for GPU-based volume rendering," *Proceedings IEEE Visualization 2003*, 2003.
[134] M. Levoy, "Display of surfaces from volume data," *IEEE Computer Graphics and Appl.*, vol. 8, no. 3, pp. 29–37, 1988.
[135] A. Van Gelder and K. Kim, "Direct volume rendering with shading via three-dimensional textures," in *Proc. 1996 Symp. on Volume Visualization*, Piscataway, NJ, 1996, pp. 23–30.
[136] B. Reitinger, A. Bornik, R. Beichel, and D. Schmalstieg, "Liver surgery planning using virtual reality," *IEEE Computer Graphics and Applications*, vol. 26, no. 6, pp. 36–47, 2006.
[137] N. Navab, M. Feuerstein, and C. Bichlmeier, "Laparoscopic virtual mirror—New interaction paradigm for monitor based augmented reality," in *Virtual Reality*, Charlotte, NC, Mar. 2007, pp. 43–50.
[138] S.-A. Ahmadi, T. Sielhorst, R. Stauder, M. Horn, H. Feussner, and N. Navab, "Recovery of surgical workflow without explicit models," in *Proc. Int. Conf. Medical Image Computing and Computer Assisted Intervention (MICCAI)*, 2006, pp. 420–428.
[139] C. Bichlmeier, F. Wimmer, H. S. Michael, and N. Nassir, "Con-textual anatomic mimesis: Hybrid in-situ visualization method for improving multi-sensory depth perception in medical augmented reality," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, Nov. 2007, pp. 129–138.
[140] D. Kalkofen, E. Mendez, and D. Schmalstieg, "Interactive focus and context visualization for augmented reality," in *Proc. IEEE and ACM Int. Symp. on Mixed and Augmented Reality (ISMAR)*, 2007.
[141] C. Pettey and L. Goasduff, *Emerging Technologies Hype Cycle*. Stamford, CT: Gartner, 2006.

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