

Applications of Augmented Reality in the Operating Room

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1 Introduction

1.1 Minimally invasive interventions

Most surgical procedures and therapeutic interventions have been traditionally performed by gaining direct access to the internal anatomy, using direct visual inspection to deliver therapy and treat the conditions. In the meantime, a wide variety of medical imaging modalities have been employed to diagnose the condition, plan the procedure and monitor the patient during the intervention; nevertheless, the tissue manipulation and delivery of therapy has been performed under rather invasive incisions that permit direct visualization of the surgical site and ample access inside the body cavity. Over the past several decades, significant efforts have been dedicated to minimizing invasiveness associated with surgical interventions, most of which have been possible thanks to the developments in medical imaging, surgical navigation, visualization and display technologies.

1.2 Augmented, virtual and mixed realities

In parallel with the aspirations toward less invasive therapy delivery on the medical side, many engineering applications have been employing computer-generated models to design, simulate and visualize the interaction between different components within an assembly prior to the global system implementation. One such approach has focused on complementing the user's visual field with information that facilitates the performance of a particular task – a technique broadly introduced and described by Milgram *et al.* as “augmenting natural feedback to the operator with simulated cues” (Milgram *et al.* 1994) and later becoming known as augmented reality (AR).

While the term *augmented reality* may be used somewhat loosely and in a more inclusive sense than it had originally been intended, it refers to visualization environments that combine real-world visualization with computer-generated information aimed to show information that direct vision cannot, resulting in a more comprehensive, enhanced view of the real world. The term *mixed reality* has been suggested as a better descriptor of such environments, as, depending on the extent of real and computer-generated information, the resulting environments can lie anywhere on the spectrum of the *reality-virtuality continuum* (Kaneko *et al.* 1993; Metzger 1993; Milgram and Kishino 1994; Takemura and Kishino 1992; Utsumi *et al.* 1994).

The real component of a typical mixed reality environment may consist of either a direct view of the field observed by the user's eyes (i.e., optical-based AR), or a view of the field captured using a video camera and displayed to the user – video-based AR. As synthetic (i.e. computer-generated) data is added to the environment, the mixed reality may become less of a traditional

augmented reality and more of an *augmented virtuality*, yet still sufficiently different from a *fully immersed virtual reality* environment, in which the user has no access to the real-world view.

Initial applications of such visualization techniques have been adopted in response to efforts in facilitating task performance in industry. While at first, computer-generated models were displayed on screens and available to the workers as “guides”, a more revolutionary approach resorted to the use of see-through displays mounted on head-set devices worn by the workers. This approach enabled the superposition of the computer models onto the real view of the physical parts (Caudell 1994), hence facilitating the worker’s task by truly augmenting the user’s view with computer-simulated cues.

1.3 Augmenting visualization for surgical navigation

Although originally designed and implemented for industrial applications, mixed reality visualization environments soon experienced traction in the medical world, motivated primarily by the goal to improve clinical outcome and procedure safety by improving accuracy and reducing variability, reduce radiation exposure to both patient and clinical staff, as well as reduce procedure morbidity, recovery time and associated costs. In addition, the challenges associated with the trend toward minimally invasive procedures quickly revealed themselves, in terms of surgical navigation and target tissue manipulation under restricted access conditions and limited vision, and hence the need for adequate intuitive visualization became critical for the performance of the procedure.

Computers have become an integral part of medicine, enabling the acquisition, processing, analysis and visualization of medical images and their integration into diagnosis and therapy planning (Ettinger et al. 1998), surgical training (Botden and Jakimowicz 2009; Feifer, Delisle, and Anidjar 2008; Kerner et al. 2003; Rolland, Wright, and Kancherla 1997), pre- and intra-operative data visualization (Koehring et al. 2008; Lovo et al. 2007; Kaufman et al. 1997) and intra-operative navigation (Nakamoto et al. 2008; Teber et al. 2009; Vogt et al. 2004; Vosburgh and San José Estépar 2007). These technologies have empowered clinicians to not only perform procedures that were rarely successful decades ago, but also embrace the use of less invasive techniques in an effort to reduce procedure morbidity and patient trauma.

Besides providing faithful diagnosis, medical imaging has also enabled a variety of minimally invasive procedures; however, the success of the procedure depends upon the clinician’s ability to mentally recreate the view of the surgical scene based on the intra-operative images. These images provide a limited field of view of the internal anatomy and also feature lower quality than the pre-operative images used for diagnosis. Moreover, depending on the employed imaging modality, the surgical instruments used during therapy may not be easily visible in the intra-operative images, raising the need for additional information.

To provide accurate guidance while avoiding critical anatomical structures, several data types acquired from different sources at different stages of the procedure are integrated within a common image guidance workflow. High-quality pre-operative images and anatomical models are employed to provide the “big picture” of the internal anatomy that help the surgeon navigate from the point of access to the target to be treated, serving as a road map. The employed surgical tools are typically instrumented with tracking (i.e. localization) sensors that encode the tool position and orientation, and, provided the patient anatomy is registered to the pre-operative

images/models (i.e. image/model-to-patient registration typically achieved via the tracking system), the virtual representation of the surgical instruments can be visualized in the same coordinate system as the road map, in a similar fashion as using a GPS navigation system to obtain positioning information along a route. To compensate for the limited intra-operative faithfulness provided by the “slightly outdated” pre-operative data, intra-operatively acquired images are also integrated into the guidance environment to provide accurate and precise target identification and on-target instrument positioning based on real-time information. Following fusion of pre- and intra-operative images and instrument tracking information, the physician performs the tool-to-target navigation using the pre-operative images/models augmented with the virtual tool representations, followed by the on-target instrument positioning under real-time image guidance complemented by real-time instrument tracking.

The multi-modality guidance and navigation information can be displayed to the surgeon via traditional 2D display screens available in the interventional suites, in the form of an augmented reality display, either directly overlaid onto the patient’s skin (i.e. optical-based AR) or by augmenting a video display of the patient (i.e., video-based AR), via tracked head-mounted (stereoscopic) displays or recently developed and commercially available 3D displays (Linte et al. 2013). Less common modes of augmented tactile and auditory feedback are also in use and will be described.

2 Image guidance infrastructure

Having set the stage, we now briefly present the key technologies involved in the development of medical navigation guidance systems (Yaniv and Cleary 2006; Cleary and Peters 2010; Peters and Cleary 2008), including: (1) medical imaging; (2) segmentation and modeling; (3) localization and tracking; (4) registration; and (5) visualization and other feedback methods.

2.1 Medical imaging

In the context of medical augmented reality, images may represent either the real or virtual part of the environment, depending on their source and acquisition time. Information obtained from pre-operative images, such as computed tomography is often displayed as virtual models of the anatomy, while real-time intra-operative imaging, such as endoscopic video, would constitute the real component. High quality pre-operative images are typically acquired for diagnostic purposes and traditionally their value was minimal during the intervention. Pre-operative diagnostic imaging modalities include Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) for anatomical imaging, and Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) for functional imaging. Intra-operative imaging modalities include X-ray fluoroscopy, Cone-Beam CT (CBCT), ultrasound (US), and video endoscopy, all of which provide anatomical imaging. A more recent addition is a commercial system for intra-operative SPECT which is part of an AR system which will be describe later on.

2.2 Segmentation and modeling

Following their acquisition, the datasets can be quite large, making them challenging to manipulate in real time, especially when not the entire extent of the data is required for a specific application. A common approach is to segment the information of interest and generate models that provide interactive visualization in the region of interest. A large number of approaches to image segmentation have been developed. These can be divided into low level and model based approaches. The most common low level segmentation approach is thresholding, which is readily applicable for segmenting bone structures in CT. Often combinations of multiple low level operations are used for specific segmentation tasks, but these are not generalizable. Model based approaches have been more successful and generalizable. Among others these include deformable models, level set based segmentation, statistical shape and appearance models, and more recently statistical methods for segmenting ensembles of organs or structures using models of organ variation and the spatial relationships between structures.

2.3 Instrument localization and tracking

Considering the surgical scene is not directly visible during most minimally invasive interventions, the position and orientation of the surgical instrument with respect to the anatomy must be precisely known at all times. To address this requirement, spatial localizers have become an integral part of image-guided navigation platforms, enabling the tracking of all interventional tools within the same coordinate system attached to the patient. The common tracking technologies found in the medical setting are either optical or electromagnetic. These are standard devices with well understood advantages and limitations. Broadly speaking, optical systems are highly accurate but require an unobstructed line-of-sight between the cameras and markers. As a result, these systems are appropriate for tracking tools outside the body or rigid tools with the markers mounted outside the body. Electromagnetic tracking systems are accurate and can track both rigid and flexible tools inside and outside the body. However, these systems are susceptible to measurement distortions in the presence of ferromagnetic materials. A less common tracking approach that is gaining traction is to use the medical images, endoscopic video or US, to track tools and anatomical structures in real-time. Currently, this approach is still limited to prototype research systems.

2.4 Registration and data fusion

Registration is the enabling technology for spatial data integration and it plays a vital role in aligning images, features, and/or models with each other, as well as establishing the relationship between the virtual environment (pre- and intra-operative images and surgical tool representations), and the physical patient. The most common registration approach found in the clinical setting is rigid registration using a paired-point approach. This is the only registration method that has an analytic solution. In some cases point identification and pairing is performed automatically and in some manually. Non rigid registration algorithms are also in use but they all require some form of initialization. While we most often judge registration algorithms solely based on their accuracy, in the clinical setting one must also take into account the computation time, robustness and amount of user interaction. The combination of these constraints determines

if an algorithm is truly applicable in a specific setting. As an example, a 2 mm registration error may be sufficiently accurate for one procedure, but not for another.

2.5 Data visualization and feedback method

Once all images and segmented structures are available, along with the spatial relationships between anatomy and devices, this information needs to be displayed to the clinician. Most often this is done visually, either using orthogonal multi-planar display of the 3D images, surface renderings of segmented structures, volume rendering of the anatomy, or non-photorealistic rendering of the objects, or less common options, including tactile feedback or auditory feedback. The choice of feedback or rendering method should not be based on subjective criteria, such as whether the operator prefers a specific visualization, but rather on the operator's performance on the task at hand given the specific feedback mechanism.

3 Guided Tour of AR in the Operating Room

3.1 Understanding the OR requirements

Developing an AR guidance system for the operating room is a challenging task. In this high risk setting, guidance systems are expected to exhibit robust behavior with intuitive operation and without interfering with the correct functionality of multiple other devices that are concurrently in use. One such example is the performance and effect of using infrared based optical tracking, the most common tracking approach currently found in the clinical setting. It is well known that surgical lights and lights used by operating microscopes can reduce tracking accuracy (Langlotz 2004), on the other hand the infrared light emitted by the tracking device has been shown to affect the measurements recorded by pulse oximeters (Mathes et al. 2008). As a consequence, when developing an AR system for the clinical setting, a holistic approach should be taken to identify all potential effects of the AR system on other equipment and vice versa. Finally, given the highly regulated safety domain, transition into clinical care requires adherence to the development practices specified by regulatory agencies (e.g. US Food and Drug Administration, Health Canada etc.).

Most likely these challenges are in part the reason that there is a significant gap between the number of systems developed in the laboratory setting and those that are able to transition into clinical care - a gap that is often referred to as "the valley of death" (Coller and Califf 2009). It is much harder to get a system into the clinic than to develop a prototype in the laboratory and evaluate it on phantoms, animal models, or a small number of patients. We thus divide our tour of AR in the OR in two parts: systems that are commercially available and systems that are laboratory prototypes.

3.2 Commercially Available Systems

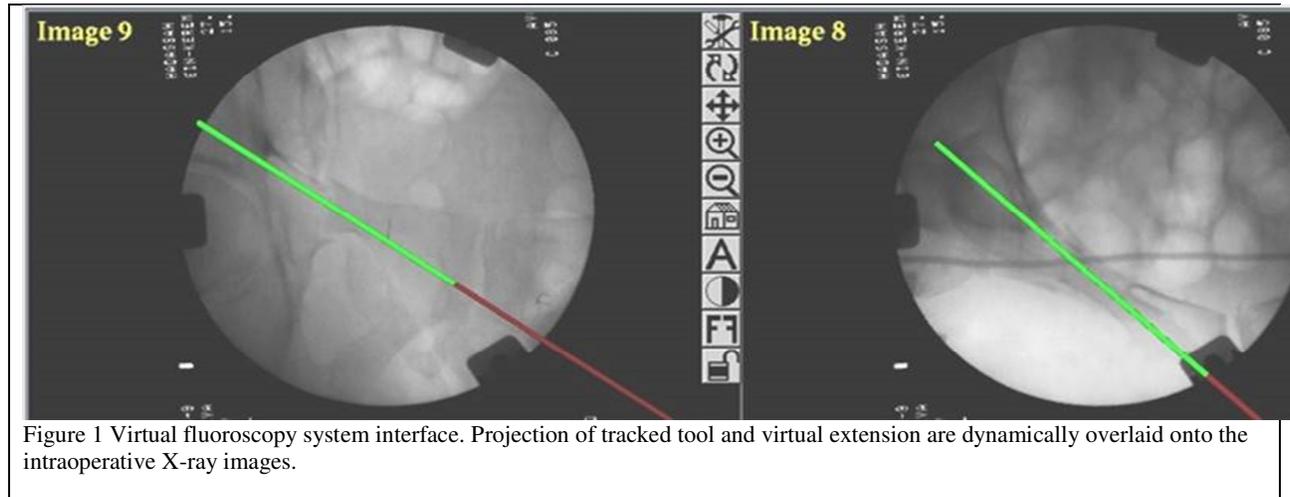


Figure 1 Virtual fluoroscopy system interface. Projection of tracked tool and virtual extension are dynamically overlaid onto the intraoperative X-ray images.

3.2.1 Augmented X-ray guidance

One of the first commercially available navigation systems was for all intents and purposes an AR system. The system augmented fluoroscopic X-ray images, displayed on a standard screen, by projecting iconic representations of tracked tools, as shown in Figure 1. Among others, these systems were available as ION Fluoronav StealthStation (Medtronic, USA), and Fluologics (Praxim, France). This form of augmentation was originally introduced in orthopedics as virtual fluoroscopy (Foley, Simon, and Rampersaud 2001). Prior to the introduction of this system, the location of a tool relative to the anatomy was performed by acquiring multiple X-ray images from different poses that the physician used to create a 3D mental map. To monitor dynamic processes, e.g. a drill trajectory, imaging was repeated multiple times at discrete intervals. As a result the patient and medical staff are exposed to a non-negligible amount of ionizing radiation, with accuracy dependent upon the physician's skill at interpreting the images. As such, virtual fluoroscopy systems mimicked the standard practice without the need for repetitive imaging and provided continuous updates by calibrating the X-ray device and tracking it and all tools. Instead of acquiring images at multiple discrete intervals, the same set of images is used to provide continuous feedback. For each X-ray image the projection parameters and imager pose are known. The tools are continuously tracked using an optical system and their representations are then projected onto the X-ray images, similar to continuous X-ray fluoroscopy. It should be noted that the end result is still highly dependent on the physician's ability to interpret these 2D projection images. These systems were shown to provide more accurate results than traditional fluoroscopy while reducing radiation exposure (Merloz et al. 2007). Unfortunately, they also resulted in longer operating times and since their introduction, they have fallen out of favor, with physicians shifting towards other forms of navigation guidance (Mavrogenis et al. 2013).

3.2.2 Augmented ultrasound guidance

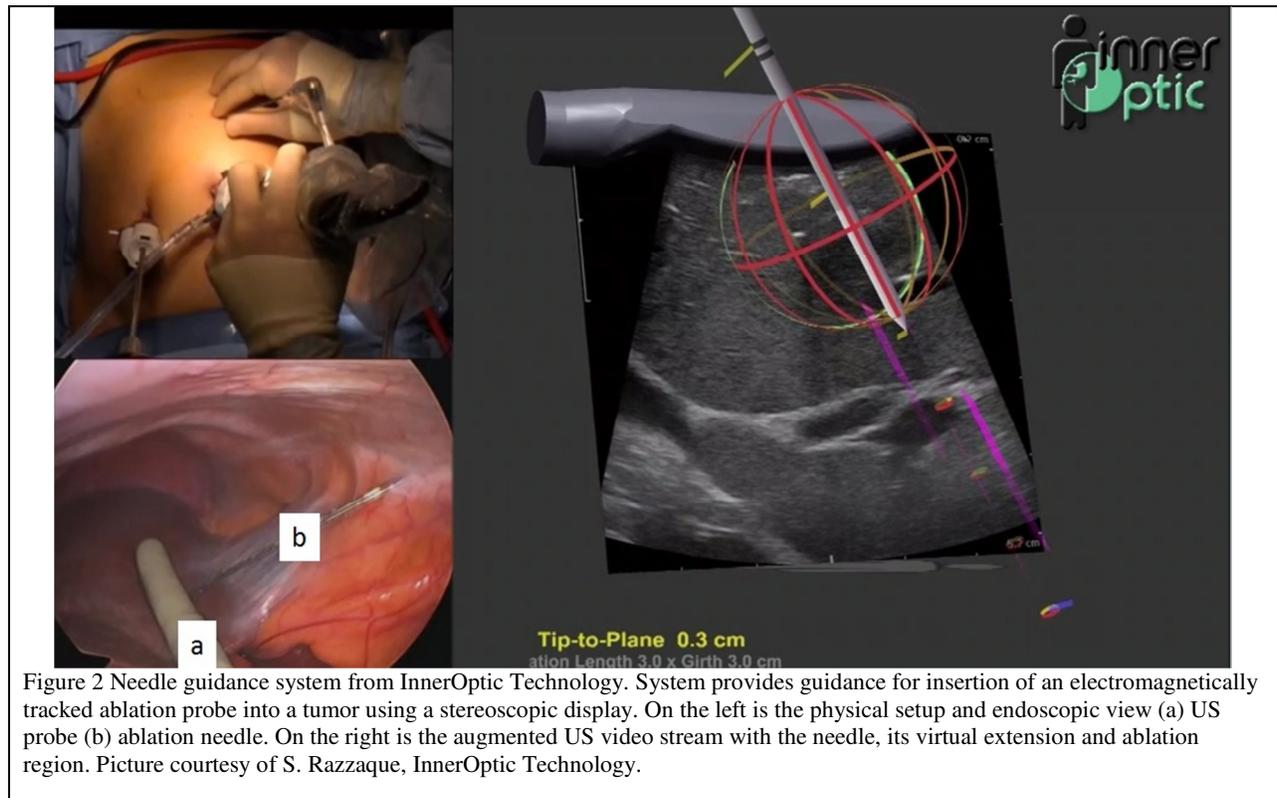


Figure 2 Needle guidance system from InnerOptic Technology. System provides guidance for insertion of an electromagnetically tracked ablation probe into a tumor using a stereoscopic display. On the left is the physical setup and endoscopic view (a) US probe (b) ablation needle. On the right is the augmented US video stream with the needle, its virtual extension and ablation region. Picture courtesy of S. Razzaque, InnerOptic Technology.

A similar approach has been recently used in the context of Ultrasound (US) guidance for procedures requiring needle insertion. These systems augment the US video stream, displayed on a standard screen, with iconic representations of the needle. The challenges addressed stem from the nature of 2D US. This tomographic modality limits the needle insertion to the plane defined by the image. In addition, identifying the location of the needle tip in the image is not trivial due to the noisy nature of US images. AR guidance systems are thought to facilitate in-plane needle insertion accuracy and enable out-of-plane insertions by augmenting the US image. When working in-plane, the needle location and a virtual extension are overlaid onto the image. When working out-of-plane, a graphic denoting the intersection of the needle trajectory with the imaging plane is overlaid onto the image. These systems use electromagnetic tracking to localize the US probe and customized needles with embedded sensors. Among others, this class of systems is available as the SonixGPS (Ultrasonix, Canada), and LOGIQ E9 (GE Healthcare, USA), and a defunct product the US Guide 2000 (UltraGuide, Israel). These systems have been used to guide lesion biopsy procedures (Hakime et al. 2012), tumor ablations (Hildebrand et al. 2007), liver resection (Kleemann et al. 2006), and for regional anesthesia (Wong et al. 2013; Umbarje et al. 2013). A limiting factor, however, is that these systems require customized needles with embedded sensors or external adaptors rigidly attached to the needle as used in the UltraGuide system. To address this issue, the Clear Guide ONE system (Clear Guide Medical, USA)¹ uses a similar augmentation approach, but does not require customized needles; instead, it uses a device mounted directly onto the US probe, which includes a structured light system to

¹ Not yet approved for clinical use.

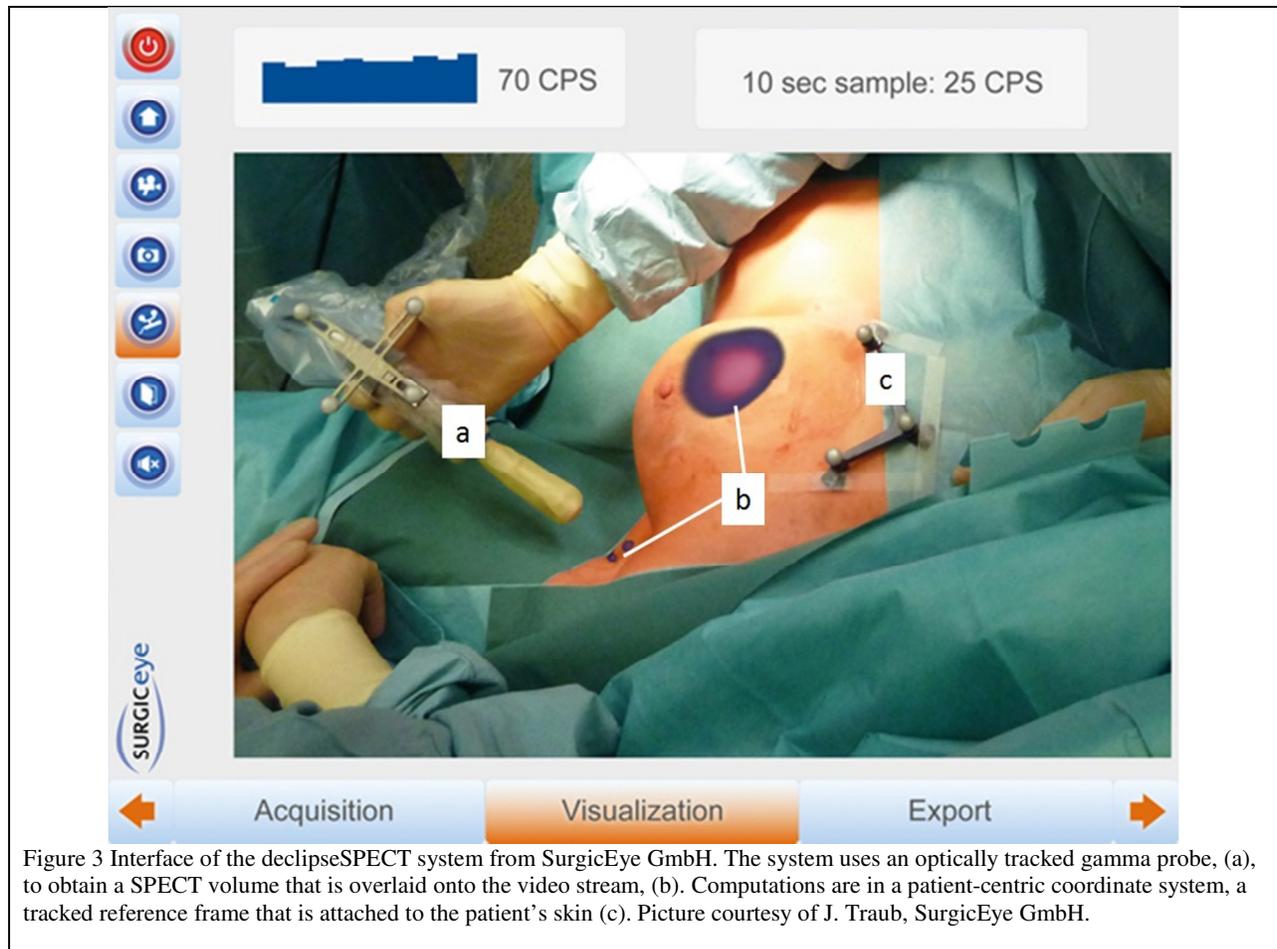
track the needle and a combination of optical and inertial sensors for tracking the US probe (Stolka et al. 2011).

Finally, a different approach to augmenting the user's perception is provided by the AIM and InVision, systems (InnerOptic Technology, USA). These use electromagnetic and optical tracking respectively, with augmentation provided via a stereoscopic display and a realistic representation of the needle. The operator is required to wear polarized glasses to perceive a fully 3D scene. These systems have been clinically used for delivering ablative therapy (Sindram et al. 2010; Sindram et al. 2011). Figure 2 shows the physical setup and augmented guidance view.

3.2.3 Augmented video and SPECT guidance

The systems described above are used to directly guide the intervention with AR being the key technical component. The declipseSPECT (SurgicEye GmbH, Germany) system uses AR to guide data acquisition and clinical decision making, although it is not the system's key novel aspect. The clinical context is the use of nuclear medicine in the surgical setting. A radiopharmaceutical tracer (i.e., a ligand linked to a gamma ray emitting substance) is injected into the blood stream and binds to tumor cells more readily than to normal cells, increasing the concentration of radiation emitting substance in the tumor. A gamma probe is then used to localize the region exhibiting higher radiation counts. Previously, localization was done in a qualitative manner, with gamma probes used to evaluate the presence of radioactive material via continuous auditory and numerical feedback (Povoski et al. 2009), providing limited knowledge about the spatial distribution of the tracer. The novelty of the declipseSPECT system consists of the reconstruction of a 3D volume based on the concentration of radioactive tracer measured with an optically tracked, handheld, gamma probe. Hence, the system does the job of a SPECT imaging system using a handheld device rather than the large diagnostic SPECT machine that cannot be used in the operating room setting. To provide AR guidance, the system combines a video camera with a commercial optical tracking system. This combination device is calibrated during assembly. Once calibrated any spatial information known in the tracking system's coordinate frame is readily projected onto the video.

As the quality of the 3D SPECT reconstruction is highly dependent on the data gathered with the tracked gamma probe, the system displays the amount of information acquired in the region of interest overlaid onto the video stream of the patient. This information guides the surgeon to place the gamma probe at locations that have insufficient measurements. Once the SPECT volume is computed, its projection is overlaid onto the video of the patient as shown in Figure 3. This overlay guides the surgeon during biopsy or resection of the tumor (Navab et al. 2012). The system was initially evaluated in a study including 85 patients undergoing lymph node biopsy after being diagnosed with invasive breast cancer (Wendler et al. 2010). The study identified the correlation between the quality of the 3D reconstruction and the quality of data acquisition, emphasizing that better acquisitions resulted in improved guidance.



Having described three forms of commercially available AR systems, we point out that all three share an important characteristic: they do not involve registration. These systems are based on calibration of the imaging device (X-ray, US, video camera) with respect to a tracking system. The augmented video consists of intra-operative imaging overlaid with additional data also acquired intra-operatively; the lack of pre- to intra-operative registration is an important aspect in the clinical setting, as the registration often disrupts and slows the clinical workflow, significantly reducing the chances of user acceptance.

3.2.4 Augmented endoscopic video guidance

A guidance system that does require registration of preoperative data is the Scopis Hybrid Navigation system (SCOPIS Medical, Germany), developed in the context of Ear-Nose-Throat (ENT) surgery. This system uses a pre-operative CT volume of the patient in which structures of interest, surgical planning information such as desired osteotomy lines, and targets are defined. Both the CT and a live endoscopic video stream are used to guide the surgeon (Winne et al. 2011). Intra-operatively, the CT is registered to the patient using rigid registration based on corresponding points identified in the CT and on the patient. The calibrated endoscope is then tracked using either optical or electromagnetic tracking, and the information defined pre-

operatively in the CT coordinate system is overlaid onto the video stream. To strike a balance between overlaying information onto the image and obscuring the anatomy, the system overlays information in a minimalistic manner, using outlines as opposed to solid semi-transparent objects. An interesting feature of endoscopic images is that they exhibit severe barrel distortion. This is a feature associated with the lenses used in endoscopes that are required to provide a wide angle view. Thus, to augment endoscopic video, one must either correct the distorted images or distort the projected data prior to merging the two information sources. The approach adopted by the Scopis system is to distort the projected data, an approach consistent with the understanding that clinicians prefer to view the original unprocessed images, as well as also more computationally efficient.

All commercially available AR systems described so far use standard or stereoscopic 2D screens to display the information, most likely due to the availability of screens in the clinical setting, and the familiarity of clinicians with this mode of interaction. Stepping into the modern day interventional setting, one immediately observes that the medical staff focuses on various screens, while almost no one looks directly at the patient. This approach is not ideal, as it poses a challenge for hand eye coordination, a known issue both in US guided needle insertion (Adhikary, Hadzic, and McQuillan 2013) and laparoscopic surgery (Wilson, Coleman, and McGrath 2010), and tentatively addressed by some AR systems described in the following section.

3.2.5 Augmented tactile feedback

An AR domain often overlooked is haptic augmented reality, using tactile feedback to augment the user's performance. In orthopedics, the concept of augmenting an operator's tactile experience was introduced in the context of bone milling for partial or total knee replacement using cooperative control of a robotic device. The original robots included the Acrobot (Acrobot Ltd, UK) and RIO (MAKO Surgical Corp., USA)², both of which involved the surgeon manually moving a robotically held milling tool with the robot providing haptic feedback, allowing the operator to freely move the tool in certain locations and preventing motion in others (Rodriguez et al. 2005) (Lang et al. 2011). The regions are defined in a planning phase and do not correspond to physical obstacles, but rather consist of bone regions where the robot should move freely, and others where it should not. This form of defining virtual obstacles is referred to in the robotics literature as virtual fixtures (Rosenberg 1993). Using these constraints the surgeon is able to perform milling through a small incision executing the pre-operative plan specified on a CT scan of the knee. This cooperative approach is better suited for clinical acceptance because the surgeons stay in control of the process while their accuracy is improved and variability is reduced. It should be noted that these systems require highly accurate registration between the robot and the boney structures, as no intra-operative imaging is used during the workflow. Registration is performed by attaching a pointer tool with known geometry to the robot and digitizing points on the bone surface. These points are registered to the bone surface defined in the CT volume. To maintain a valid registration throughout the procedure, the anatomy is either immobilized or it is instrumented with optically tracked reference markers. Initial clinical use appears promising (Lonner, John, and Conditt 2010), with more accurate and less variable

² The Acrobot and RIO systems are currently owned by Stryker Corp.

implant placements achieved with the robotic device. While the technical goal of these systems may have been achieved, it is yet to be determined if they make a clinical difference. Will the improved accuracy and reduced variability improve the implant function and longevity? The requirement for almost perfect registration has been identified as a key issue with the use of the RIO system, and along with robot positioning, these constraints are cited as the main reasons for longer surgery times (Banger, Rowe, and Blyth 2013).

3.3 Laboratory prototypes

The number of laboratory AR systems is exceedingly large as compared to the few that have made it into the commercial domain. The following sections provide brief descriptions of such systems. Most notably, all of these prototypes except one are based on visual augmentation and are therefore divided into sub-categories based on their display technology: a screen, a medical binocular system, a Head Mounted Display (HMD), a half silvered mirror display, or direct projection onto the patient.

To start with an exception, the *virtual reality* system for guiding endoscopic skull base surgery that also incorporates auditory augmentation (Dixon et al. 2014). This system provides auditory cues in addition to virtual reality views of the underlying anatomy. Critical anatomical structures are segmented from an intra-operative CBCT data set that are rigidly registered to the patient. Structure and distance dependent auditory cues are used to alert the operator of proximity to specific critical structures. The system was evaluated by seven surgeons who preferred the auditory alarms be customizable, with the option of turning them off once the location of the critical structures had been identified using the endoscopic or virtual reality views. This speaks to the need for context awareness in these systems, as discussed in Section 4.

In this tour, similar systems are grouped and presented in chronological order according to their development and cited relevant publications in that specific group.

3.3.1 Screen based display

Stepping into a modern operating room one immediately notices multiple screens displaying various pre- and intra- operative data. The second observation is that most of the time the clinical staff is looking at the screens and not directly at the patient. Thus, introducing an additional screen is clinically acceptable, possibly explaining why this display choice is the most common approach used by AR systems.

It should be noted that this tour *does not* include systems that utilize a separate screen approach – one screen showing a virtual reality scene depicting the underlying spatial relationships between surgical tools and anatomy with additional screen(s) showing the physical scene via intra-operative imaging (e.g. endoscopic or US video streams (Ellsmere et al. 2004)). This approach relies on the operator to integrate the information from the virtual and real worlds and thus should not be classified as an AR system, but a VR system in conjunction with real-time imaging and will not be discussed.

One of the first image-guided navigation systems for neurosurgical procedures was the system presented in (Grimson et al. 1996). This system augmented video from a standard camera with

structures segmented from pre-operative CT or MR, rigidly registered to the intra-operative surgical scene. The surgeon physically traced contours of the relevant structures onto the patient's scalp using the augmented video. The system did not include tracking of the patient or tools, assuming that the patient was stationary until all structures were physically marked. A related system for liver tumor ablation was described in (Nicolau et al. 2009). This system overlaid models of the liver segmented from CT onto standard video. Rigid registration was used to align the CT acquired at end-exhalation with the physical patient. As the liver moves and deforms with respiration, the registration and guidance information were only valid and therefore used at end-exhalation. In this system, the distal end of the ablation needle was optically tracked using a printed marker, assuming a rigid needle, with a fixed transform between the needle's tracked distal end and its tip. Following clinical evaluation, it was determined that the needle deflection was not negligible in 25% of the cases, an issue which can be mitigated by using electromagnetic tracking and embedding the tracked sensor close to the needle's tip.

A system that overlays a rendering of tumor volume onto standard video without the need for registration was described in (Sato et al. 1998). This system was developed in the context of breast tumor resection. A standard video camera and a 2D US probe are optically tracked and a 3D US volume was acquired with the tracked US, therefore providing information on the tumor location relative to the tracked camera. The system assumes a stationary tumor, which is achieved by suspending the patient's respiration for a short period.

A more recent system aiming to improve puncture site selection for needle insertion in epidural anesthesia was described in (Al-Deen Ashab et al. 2013). Using an optically tracked US probe the system creates a panoramic image of the spinal column and identifies the vertebra levels. The optical tracking system also provides a live video stream and the calibration parameters for the video camera, which were used in conjunction with the known 3D location of the vertebrae from US to overlay corresponding lines onto the video of the patient's back without the need for registration. The overlay is iconic, with lines denoting the vertebra location and anatomical name.

Finally, a system that uses AR to guide the positioning of a robotic device was described in (Joskowicz et al. 2006). This system is used in the context of neurosurgery and relied on a pre-operative CT or MR of the head that was rigidly registered relative to a camera located in a fixed position. The location of the desired robot mounting is projected onto the camera's video stream, allowing the user to position the physical mount accordingly.

Several groups have proposed the use of a tracked standard video camera to guide maxillofacial and neurosurgery procedures (Weber et al. 2003; Mischkowski et al. 2006; Kockro et al. 2009; Pandya, Siadat, and Auner 2005) and more recently for guidance of kidney stone removal (Müller et al. 2013). Tracking of the camera pose is performed using either a commercial optical tracking system (Weber et al. 2003; Mischkowski et al. 2006; Kockro et al. 2009), a mechanical arm (Pandya, Siadat, and Auner 2005), or directly from the video stream using pose estimation (Müller et al. 2013). The camera video feed is then augmented with projections of anatomical structures segmented from pre-operative CT scans and rigidly registered to the intra-operative patient. The systems described in (Weber et al. 2003) and (Mischkowski et al. 2006) mount the camera on the back of a small hand-held LCD screen, which is equivalent to the use of a tablet with built in camera described in (Müller et al. 2013). In these systems the operator positions the screen between themselves and the patient as if looking through a window, providing an intrinsic rough alignment of the operator and camera viewing direction, ensuring that the augmented information overlaid onto the visible surface is in the correct location relative to the operator's viewing angle.

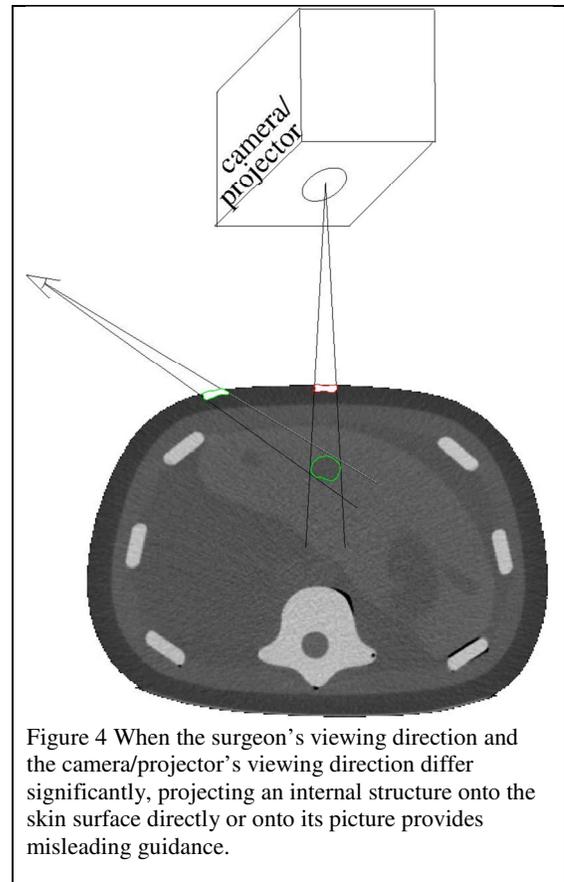


Figure 4 When the surgeon's viewing direction and the camera/projector's viewing direction differ significantly, projecting an internal structure onto the skin surface directly or onto its picture provides misleading guidance.

In the system described in (Kockro et al. 2009) the tracked camera is mounted inside a surgical pointer and the augmented views are displayed on a standard screen. As a consequence the camera and surgeon's viewing direction may differ significantly, resulting in erroneous perception of the location of the overlaid structures on the skin surface, as illustrated in Figure 4. This effect became apparent when surgeons attempted to use a pen to physically mark the structure locations on the patient's skin, a similar issue to that arising when projecting the underlying anatomical structures directly onto the patient (section 3.3.5).

The following group of systems augments endoscopic video with additional information acquired either pre- or intra-operatively. Before proceeding, it is worthwhile noting a unique characteristic of all endoscopic systems: they exhibit severe radial distortions. This is due to their use of fish-eye lenses, a constraint imposed by the need to have a wide field of view while minimizing the size of the tool inserted into the body, therefore requiring correction of the distorted video images or distortion of the augmented information before fusion.

An early example of augmented endoscopy was described in (Freysinger, Gunkel, and Thumfart 1997). This system was developed in the context of ENT surgery. The endoscope's path is specified on a pre-operative CT or MR. Both patient and endoscope are localized using electromagnetic tracking. The pre-operative image is rigidly registered to the patient and an iconic representation of the desired endoscope path in the form of rectangles is overlaid onto the video.

A similar system developed for guiding resection of pituitary tumors was described in (Kawamata et al. 2002). Critical structures such as the carotid arteries and optic nerves are segmented pre-operatively in MR or CT. The patient and endoscope were optically tracked and following rigid registration, all of the segmented structures are projected as wireframes onto the endoscopic image. It should be noted that this form of augmentation all but occluded the content of the endoscopic image.

A more recent development is the system for lymph node biopsy guidance presented in (Higgins et al. 2008). This system ensures the physician obtains the biopsy from the correct location, which is not visible on the endoscopic video, by overlaying the segmented lymph node identified in pre-operative CT onto the endoscopic view. A unique feature of this system is that it does not use external tracking devices; instead, the location of the endoscope is estimated by rigidly registering a virtual view generated from CT to the endoscopic video. Comparison between the real and synthetic images is performed using an information theory based metric.

Having identified intra-operative registration of soft tissue organs as a complex challenge, some groups have decided to side step this hurdle. Instead of using data from pre-operative volumetric images, these groups acquire volumetric or tomographic data intra-operatively in a manner that ensures that the pose of the endoscope is known with respect to the intra-operative coordinate system. One such system developed in the context of liver surgery was described in (Konishi et al. 2007). The system uses a combined magneto-optical tracking system to track an US probe and the endoscope. The tracked 2D US is used to acquire a volume intra-operatively when the patient is at end-exhalation. Vessels and tumor locations are volume rendered from this data and overlaid onto the endoscopic video. No registration is required as the relative pose of the US and endoscope is known in the external tracking system's coordinate frame.

Another system targeting liver tumor resection was described in (Feuerstein et al. 2008). That system employed an optical tracking system and intra-operative volumetric imaging is acquired using a CBCT machine. A contrast enhanced CBCT image is acquired before resection with the patient at end-exhalation. The structures visible in CBCT are then overlaid onto the endoscopic video so that the surgeon is aware of the location of blood vessels and bile ducts that go into and out of the liver segment of interest. Augmentation is only valid during the end-exhalation respiratory phase and prior to the beginning of resection.

A system that is not limited to guidance during end-exhalation was described in (Shekhar et al. 2010). Localization is done with an optical tracking system and intra-operative volumetric images are acquired with a CT machine whose pose relative to the tracking system is determined via calibration. To enable augmentation throughout the respiratory cycle, an initial high quality contrast enhanced volume is acquired. This volume is then non-rigidly registered to subsequently-acquired low dose CTs. The deformed structures are overlaid onto the endoscopic image. The main issue with this approach is the increased radiation exposure, making it less likely to be adopted clinically. This approach later evolved into the use of optically tracked 2D US that is continuously fused with live tracked stereo endoscopy (Kang et al. 2014). This system does not require registration and implicitly accommodates organ motion and deformation.

While the majority of endoscopy based AR systems use commercial tracking devices, the system described in (Teber et al. 2009; Simpfendörfer et al. 2011) is unique in that it uses the medical

images and implanted markers to perform endoscopic tracking. Note that this approach is invasive, as the markers are implanted into the organ of interest under standard endoscopic guidance. Retrieval of the markers is also an issue, unless the procedure entails resection of tissue and the markers are implanted in the gross region that will be removed during the procedure. An additional issue with this approach is that it assumes that the organ does not deform, limiting its applicability to a subset of soft tissue interventions. The system was utilized in radical prostatectomy and partial kidney resection. In the former application, a 3D surface model obtained from intra-operative 3D transrectal US was overlaid onto the video images, while in the latter, anatomical models were obtained from intra-operative CBCT data.

While virtual fluoroscopy as a commercial product has experienced somewhat of a fall-out from the clinic, variants of this approach that provide augmented X-ray views of registered anatomical structures have continued to be developed in research labs. In the context of orthopedic surgery, an AR system was developed to aid in the reduction of long bone fractures (Zheng, Dong, and Gruetzner 2008). This system registers cylindrical models to the two fragments of the long bone using two X-ray images. Each bone segment is optically tracked using rigidly implanted reference frames. As the surgeon manipulates the bone fragments, the image is modified based on the models without the need for additional X-rays. In the context of cardiac procedures, a variation on the virtual fluoroscopy approach is used with pre-operative data from MRI augmenting live fluoroscopy (De Buck et al. 2005; Dori et al. 2011; George et al. 2011). These procedures are traditionally guided using fluoroscopy as the imaging modality, which only enables clear catheter visualization, with the heart only clearly visible under contrast agent administration. As contrast can cause acute renal failure, the clinician has to strike a balance between the need to observe the spatial relationships between catheters and anatomy and the amount of administered contrast. Both the systems described in (De Buck et al. 2005) and (Dori et al. 2011) rigidly register the MRI data to contrast enhanced X-rays using manual alignment. While the former uses a segmented model, the latter uses a volume rendering of the MRI dataset. A system using automatic fiducial based rigid registration is described in (George et al. 2011), with the X-ray images augmented with a segmented model from MRI. It should be noted that all these systems use rigid registration with the augmented data being valid only at a specific point of the cardiac and respiratory cycles. Thus, the need for live fluoroscopy remains in clinical demand, as it reflects the dynamic physical reality with the additional augmented information that is not necessarily synchronized.

Finally, a recent method for initializing 2D/3D registration based on augmentation of fluoroscopic images was described in (Gong et al. 2013). An anatomical model obtained from pre-operative CT or MR is virtually attached to an optically tracked pointer. The operator uses the pointer to control the overlay of the model onto intra-operative fluoroscopic images of the anatomy. Overlay is performed using the projection parameters of the X-ray device. When the model is visually aligned with the fluoroscopic images, it is physically in the same location as the anatomical structure. Once alignment is visually determined, the pose of the tracked pointer yields the desired transformation. Figure 5 shows this system in the laboratory setting.

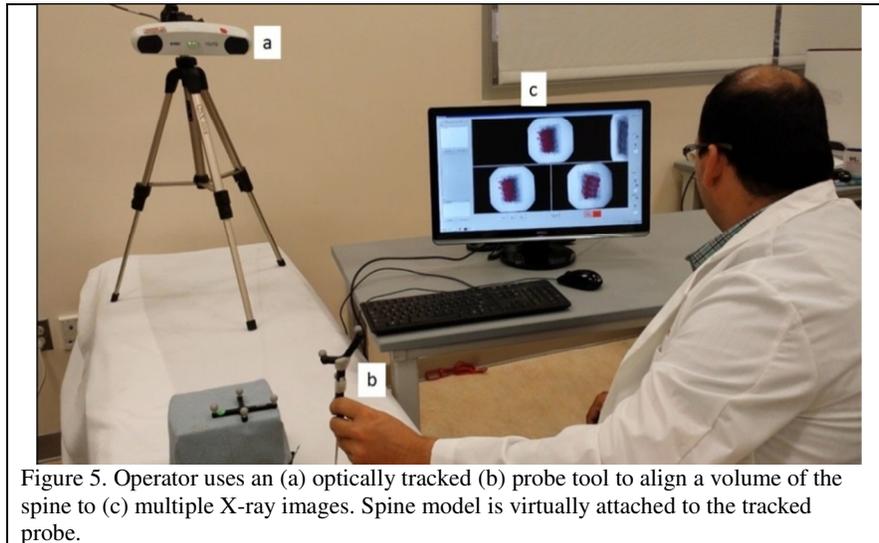
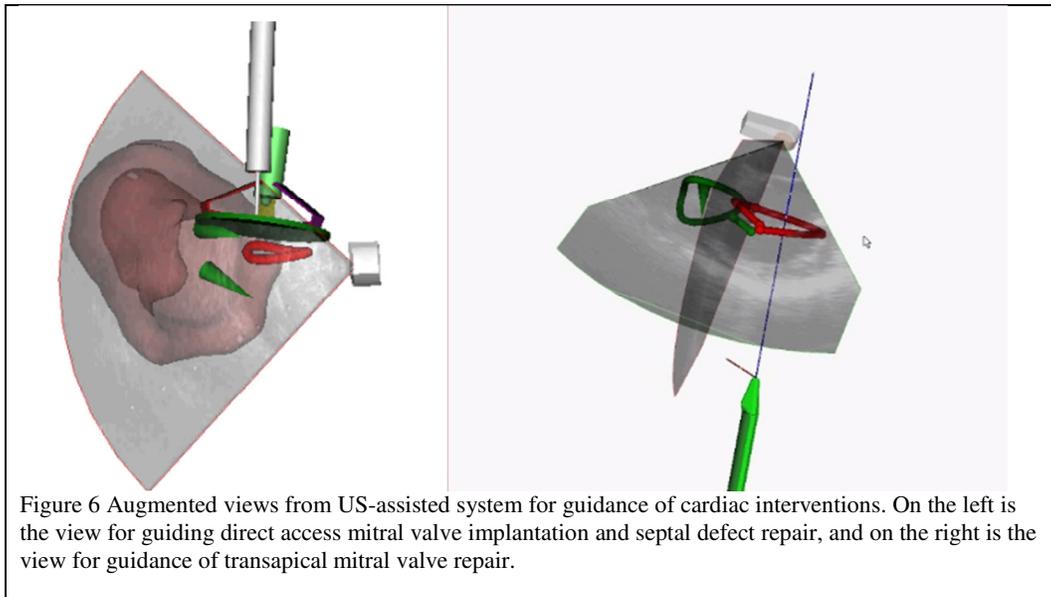


Figure 5. Operator uses an (a) optically tracked (b) probe tool to align a volume of the spine to (c) multiple X-ray images. Spine model is virtually attached to the tracked probe.

While all of the systems described above augmented fluoroscopic X-ray images, they involved cumbersome user interactions or required the use of additional hardware components such as tracking systems. This is less desirable in the intra-operative environment where space is often physically limited and time is a precious commodity. An elegant AR system combining video and X-ray fluoroscopy in a clinically appropriate form factor was described in (Navab, Heining, and Traub 2010; Chen et al. 2013). This system is based on a modified portable fluoroscopy unit, a C-arm. A video camera and a double mirror system are attached to the C-arm and calibrated such that the optical axis of the video camera and the X-ray machine are aligned. Following this one time calibration, the X-ray images are overlaid onto the video, placing them in the physical context. Thus, the exact location of underlying anatomy that is readily visible in the X-ray is also visible with respect to the skin surface seen in the video.

The last system in this category is a model-enhanced US-assisted guidance system for cardiac interventions. The system integrates electromagnetically tracked trans-esophageal US imaging providing real-time visualization, with augmented models of the cardiac anatomy segmented from pre-operative CT or MRI and virtual representations of the electromagnetically tracked delivery instruments (Linte et al. 2008; Linte et al. 2010). The anatomical models were rigidly registered to the intra-operative setting. While this registration is not accurate enough for navigation based on the pre-operative models, they provide missing context while the intra-operative US provides the live navigation guidance. The system was later adapted to an augmented display for mitral valve repair to guide the positioning of a novel therapeutic device, NeoChord, as describe in (Moore et al. 2012).



3.3.2 Binocular display

Medical binocular systems are a natural vehicle for augmented reality as they already provide a mediated stereo view to the surgeon. Thus, the introduction of AR systems into procedures utilizing these systems is more natural and has a smaller impact on the existing workflow, increasing the chances of user adoption. Unlike the screen-based display in which information is overlaid onto a single image, the systems in this category need to overlay the information on two views in a manner that creates correct depth perception.

One of the earlier systems in this category was the Microscope-Assisted Guided Interventions (MAGI) system (Edwards et al. 2000). This system was developed in the context of neurosurgery, augmenting the visible surface with semi-transparent renderings of critical structures segmented in pre-operative MR. Both patient and microscope are optically tracked, with the patient rigidly registered to the intra-operative settings. Unfortunately, the depth perception created by the overlay of semi-transparent surfaces even, with highly accurate projection parameters and registration, was ambiguous and unstable (Johnson, Edwards, and Hawkes 2003). Another system that can be described as a medical Head Mounted Display (HMD) is the variscope AR (Birkfellner et al. 2003). By adding a beam splitter to a clinical head mounted binocular system, additional structures segmented from pre-operative CT are injected into the surgeon's line of sight. The surgeon's head location, tools, and patient are all optically tracked. The pre-operative data is rigidly registered to the patient with the intended use being neurosurgery applications.

The da-Vinci robotic surgical system is a commercial master-slave robotic system for soft tissue interventions (DiMaio, Hanuschik, and Kreaden 2011). The surgeon controls the system using visual feedback provided by a stereo endoscope on the patient side, with the images viewed through a binocular system on the surgeon's side, as shown in Figure 7. A number of groups have proposed to augment the surgeon's view by overlaying semi-transparent surface models onto the stereo images. Models are obtained from

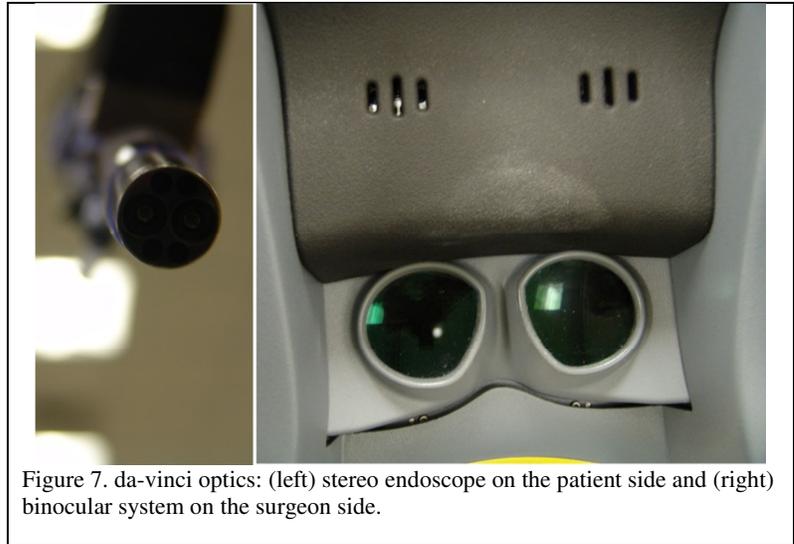


Figure 7. da-vinci optics: (left) stereo endoscope on the patient side and (right) binocular system on the surgeon side.

segmentation of CT and are rigidly registered to the intra-operative setting. Among others these include: overlay of reconstructed coronary tree for cardiac procedures using a one-time manual adjustment of the original rigid registration without any further updates (Falk et al. 2005), overlay of semi-transparent kidney and collecting system for partial kidney resection with continuous rigid registration to account for motion (Su et al. 2009), overlay of blood vessels for liver tumor resection (Buchs et al. 2013) without any updates after the initial registration³, and overlay of semi-transparent facial nerve and cochlea for cochlear implant surgery (Liu et al. 2014), again, without any updates after the initial registration.

3.3.3 Head-mounted display

Head Mounted Displays (HMDs) are in many ways equivalent to the medical binocular systems described above. They differ in several aspects, as they are not part of the current clinical setup, historically they have been rather intrusive, and the augmentation is only visible to a single user. Possibly with the newer generation of devices such as Google Glass, Epson's Moverio BT-200, and the Oculus Rift, systems utilizing such devices may be revived in the clinical setting, as they are much less intrusive.

One of the pioneering clinical AR systems did use a HMD for *in-situ* display of US images (Bajura, Fuchs, and Ohbuchi 1992) and a decade later an updated version of this system was used to provide guidance for breast biopsy (Rosenthal et al. 2002). In this system the HMD, US probe, and biopsy needle are optically tracked, with no intra-operative registration required. This guidance concept later evolved into the AIM and InVision commercial systems described above, but with the display consisting of a stereoscopic monitor as opposed to a HMD.

A system for biopsy guidance using an optically tracked HMD and needle was described in (Vogt, Khamene, and Sauer 2006; Wacker et al. 2006). The system overlays information from pre-operative or, the less common, intra-operative MR onto the field of view, and rigidly registered to the patient. A more recent, cost effective AR system for guiding needle insertion in

³ Note that the system was used on patients that were cirrhotic; the liver is rigid due to disease.

vertebroplasty was describe in (Abe et al. 2013). The system uses an outside-in based optical tracking approach using a low cost web-camera attached to the HMD. Registration is performed via visual alignment using X-ray imaging, with guidance provided via a needle trajectory planned on a pre-operative CT.

3.3.4 Semi-transparent (half-silvered mirror) display

Half silvered mirror devices overlay information in the line of sight of the operator in a manner that they perceive the augmented image in its correct spatial location. This approach allows the operator to maintain a focus on the interventional site, increasing hand-eye coordination.

One of the earlier examples of using AR in the interventional setting displayed CT data overlaid onto a physical phantom using a half silvered mirror and a stereoscopic display that alternated images between left and right eye with corresponding shutter glasses (Blackwell et al. 2000). The system was intended for educational purposes. The operators head, the display position and phantom were tracked using an optical tracking system, with the corresponding CT image of the phantom rigidly registered to its physical counterpart.

The Sonic flashlight is a system designed for guiding US based needle interventions (Stetten and Chib 2001; Chang et al. 2002; Chang, Horowitz, and Stetten 2005). A miniature display and a half silvered mirror are mounted onto a standard 2D US probe. The operator looks directly at the insertion site and sees the tomographic information overlaid onto the anatomy in a natural manner. This enhances hand eye coordination as compared to a screen based display, does not require registration or tracking and is a minimal modification of the existing clinical setup. The system was successfully used by clinicians in two clinical trials (D. Wang et al. 2009; Amesur et al. 2009). Figure 8 shows the system in use.

A similar system albeit larger scale was describe in (Fichtinger et al. 2005; Fischer et al. 2007). In this case, instead of attaching the screen and half silvered mirror to an US probe, they were attached to a CT and MR scanners. This approach provided a means for needle insertion guidance with the tomographic image being either CT or MR. It should be noted that these imaging modalities are primarily used for diagnosis and less for guidance of interventional procedures due to their costs, and, as a consequence such a device is less likely to gain widespread clinical acceptance.

The Medarpa system, developed at the Fraunhofer Institute, Germany, overlays CT data onto the patient, similar to the previous system, with the advantage that the display is mobile (Khan et al. 2006). The intended use is needle guidance for biopsy procedures. To display the relevant information, the head of the operator and the mobile display are optically tracked, while the

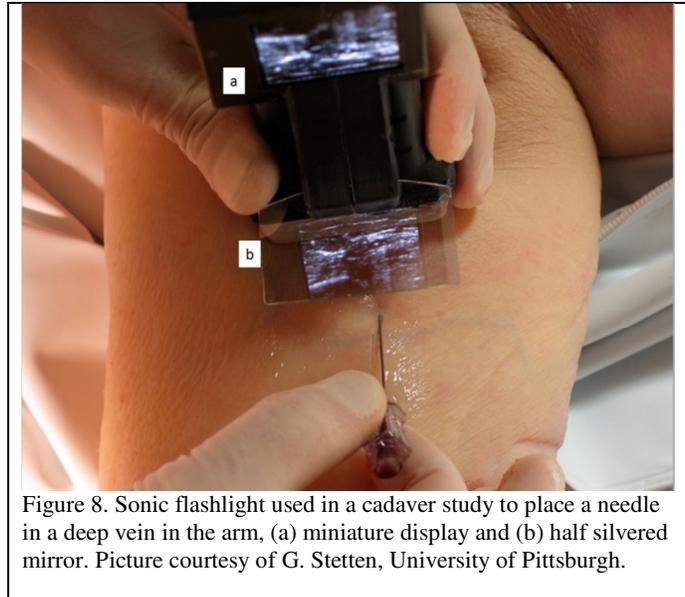


Figure 8. Sonic flashlight used in a cadaver study to place a needle in a deep vein in the arm, (a) miniature display and (b) half silvered mirror. Picture courtesy of G. Stetten, University of Pittsburgh.

needle is electromagnetically tracked. The system requires patient registration and calibration of the two tracking systems, so that the transformation between them is known. These steps are less desirable as they increase the time a procedure takes and involve increased cost and technological footprint in the interventional suite given the use of multiple tracking systems.

Finally, a unique 3D auto-stereoscopic system in combination with a half silvered mirror was described in the context of guidance of brain tumor interventions in an open MRI scanner (Liao et al. 2010) and guidance of dental interventions using CT data (Wang et al. 2014). This system is unique in itself, as it provides the perception of 3D without the need for custom glasses. This is achieved by using integral photography, placing an array of lenses in front of the screen that create the correct 3D perception from all viewing directions. In the MRI based version of the system, the image volume was rigidly registered to the patient and the integral videography device and tools were tracked optically using a commercial tracking system. In the CT-based version, the tracking and registration were customized for the procedure using an optical tracking system developed in-house with the volumetric image registered to the patient using the visible dental structures.

3.3.5 Direct patient overlay display

Directly overlaying information onto the patient became possible with the introduction of high quality projection systems that have a sufficiently small form factor. Similar to the use of a half silvered mirror, this approach facilitates better hand-eye coordination, as the surgeon's attention is not divided between a screen and the interventional site. An implicit assumption of a projection-based display is that there is a direct line of site between the projector and the patient. In the physically crowded operating room such a setup is not always feasible, as the clinical staff and additional equipment will often block the projector's field of view. An additional issue with this display approach is that it can lead to incorrect perception of the location of deep seated structures if the projection direction and the surgeon's viewing direction differ significantly, as illustrated in Figure 4.

One of the earlier projection based augmentation approaches used a laser light and the persistence of vision effect to overlay the shape of a craniotomy onto a head phantom (Glossop et al. 2003). A CT volume was rigidly registered to the phantom using an optically tracked pointer, after which the craniotomy outline defined in the CT was projected as a set of points in quick succession, creating the perception of an outline overlaid onto the skull. Another system developed in the context of craniofacial surgery overlaid borehole geometry, bone cutting trajectories and tumor margins onto the patient's head (Wörn, Aschke, and Kahrs 2005; Marmulla et al. 2005). A rigid registration was performed by matching the surface from a CT scan to an intra-operative surface scan acquired using coded light pattern.

A system for guiding needle insertion in brachytherapy, insertion of radioactive implants into tumor, was describe in (Krempien et al. 2008). The system uses a fixed projector that is utilized both for guidance, as well as to project a structured light pattern for acquiring 3D intra-operative surface structures. The intra-operative surface is rigidly registered to a pre-operative surface extracted from CT. Information is presented incrementally, first guiding the operator to the insertion point, then aligning the needle along insertion trajectory and then insertion depth. The

system used iconic information and color coding to provide guidance, while tracking both the patient and needle using a commercial optical tracking system.

A system for guiding port placement in endoscopic procedures was presented in (Sugimoto et al. 2010). A volume rendering of internal anatomical structures from pre-operative CT is projected onto the patient's skin using a projector fixed above the operating table. The CT data is rigidly registered to the patient using anatomical structures on the skin surface (e.g. umbilicus). Registration accuracy was about 5mm, with the result used as a rough roadmap helping the surgeon to select appropriate locations for port placement. The procedure itself was then guided using standard endoscopy. A similar system facilitating port placement in endoscopic liver surgery performed using the Da Vinci robotic system was described in (Volonté et al. 2011). Registration and visualization are similar in both systems. In the Da Vinci case, clinicians noted that this form of guidance was primarily useful in obese patients that required modification of the standard port locations.

The development of small form factor projectors enabled the projection of information directly onto the patient using a handheld and optically tracked pico-projector (Gavaghan et al. 2011; Gavaghan et al. 2012). This system was used to project vessels and tumor locations onto the liver surface for guiding open liver surgery, tumor localization for guiding orthopedic tumor resection, and for guiding needle insertions by projecting iconic information, cross hairs and color, to indicate location and distance from target. Pre-operative information was obtained from CT, and rigid registration was used to align this information to the intra-operative setting. This system does not take into account the viewer's pose and the associated issues of depth perception when projecting anatomical structures. Rather, it adopts a practical solution, overlaying iconic guidance information instead of projecting anatomical structures for structures that lie deep beneath the skin surface.

A more recent, fixed projector display, system that implicitly accounts for motion and deformation was described in (Szabó et al. 2013). This system overlays infrared temperature maps directly onto the anatomy. The intent is to facilitate identification of decreased blood flow to the heart muscle during cardiac surgery. The system uses an infrared camera and a projector that are calibrated, so that their optical axis is aligned. The system does not require registration as all data is acquired intra-operatively and, as long as the acquisition and projection latency is sufficiently short, it readily accommodates the moving and deforming anatomy.

4 Limitations and Challenges

The goal of AR environments in clinical applications is to enhance the physician's view of the anatomy and surgical site as a means to facilitate tool-to-target navigation and on-target instrument positioning. Nevertheless, most systems will face several challenges, some of which may delay or reflect upon their clinical acceptance.

4.1.1 Optimal information dissemination and user perception performance

Most image guidance platforms integrate data and signals from several sources, including pre- and intra-operative images, functional (i.e., electrophysiology) data and surgical tracking

information, all incorporated in a common coordinate frame and display. The operator's performance is thus dependent on their perception and interpretation of this information. Thus, even a technically optimal system is still dependent on the human observer's perception of the presented information.

One of the first publications to identify perception related issues with medical AR systems was (Johnson, Edwards, and Hawkes 2003). That work identified depth perception issues when using semi-transparent structure overlay onto the visible surface in a stereoscopic setup. A later study evaluated the effect of seven rendering methods on stereoscopic depth perception (Sielhorst et al. 2006). The best performance was achieved with semi-transparent surface rendering and when using a virtual window overlaid onto the skin surface. Others have proposed various rendering and interaction methods to improve depth perception both in stereoscopic and monocular views. In (Bichlmeier et al. 2009) the concept of using a virtual mirror is introduced. They show that by introducing a user controllable virtual mirror into the scene, the operator is able to achieve improved stereoscopic depth perception. In monocular augmented reality, (Kalkofen, Mendez, and Schmalstieg 2009) describe the use of a *focus + context* approach to improve depth perception. Edges from the *context structure* in the original image are overlaid onto the augmented scene, partially occluding the *augmented focus* information, leading to improved depth perception. A novel non-photorealistic approach for conveying depth in monocular views is described in (Hansen et al. 2010). Standard rendering methods are replaced by illustrative rendering with depth of structures conveyed by modifying the stroke thickness and style. A more recent evaluation of rendering methods for enhancing depth perception of a vessel tree structure was described in (Kersten-Oertel, Chen, and Collins 2014). Seven depth cues are evaluated with rendering using depth-dependent color and the use of aerial perspective shown to give the best depth cues.

Finally, even an ideal system from the technical and perceptual standpoint may present us with new challenges. In (Dixon et al. 2013) the issue of inattention blindness was studied. That is, by providing a compelling AR environment we are increasing the clinician's focus on specific regions while reducing their ability to detect unexpected findings nearby. In a randomized study using endoscopic AR, with the control being standard endoscopy, it was shown that the AR system lead to more accurate results, but that it significantly reduced the operator's ability to identify a complication or a foreign body that were in close proximity to the target. This is a critical issue in systems where the operator is the only person viewing the scene (e.g. systems using medical binocular) where no other member of the clinical staff can alert them to such issues.

4.1.2 Accommodation for tissue motion and organ deformation

Most interventions involving soft tissues are prone to anatomical differences between the pre-operative image dataset, and any anatomical models derived from these data, and the intra-operative anatomy. Most such changes are simply due to a different patient position or "tissue relaxation" when accessing the internal organs. To better estimate and/or account for tissue and organ deformation that is not reflected in the typical rigid-body image-to-patient registration performed prior to the start of a typical image-guided procedure, several techniques for surface

estimation and tracking have been explored (Maier-Hein et al. 2013). Stoyanov *et al.* proposed image stabilization and augmentation with surface tracking and motion models, using the operator's gaze to identify the region that should be stabilized (Stoyanov et al. 2008). A recent survey of the current state of the art AR systems for partial kidney resection, (Hughes-Hallett et al. 2014), noted that accounting for organ and tissue deformation remains a major research challenge.

4.1.3 Compatibility with clinical workflow and environment

Most interventional navigation systems that have been successfully embraced into the clinic do not require a great deal of new equipment, and integrate easily with the existing equipment in the interventional suite, in a context-aware manner. In addition, more technology leads to more data sources and more data being displayed, which in turn may become harmful by occluding information visible in the intra-operative images. One approach to limit the overwhelming technological foot-print and its impact on the interventional workflow and data interpretation is via context-aware AR systems (Katić et al. 2013; Katić et al. 2014). This requires that we study the existing procedure workflow, identifying different stages using input from various unobtrusive sensors (Nassir Navab et al. 2007), as well as content of the intra-operative medical images, and the relative locations of tools and anatomy reported by a tracking system. In (Jannin and Morandi 2007), the authors define and use an ontology to model surgical procedures by facilitating identification of parameters that enable prediction of the course of surgery. In their recent work, Padoy *et al.* proposed the use of hidden Markov models and dynamic time warping (Padoy et al. 2012) to identify surgical phases, an approach similar to the one proposed in (Bouarfa, Jonker, and Dankelman 2011) that relies on embedded Bayesian Hidden Markov Model to identify surgical phases.

4.1.4 Cost-effectiveness

Based on past performance, introduction of new technologies into the operating room has more often increased the cost of providing healthcare (Bodenheimer 2005). Government agencies are aware of this as reflected by the goals of the affordable healthcare act in the United States which aims to reduce healthcare costs (Davies 2013). From a financial perspective, only a few studies have focused on evaluating the cost-effective use of virtual reality image-guidance and robotic systems (Novak, Silverstein, and Bozic 2007; Swank et al. 2009; Desai et al. 2011; Costa et al. 2013; Margier et al. 2014), and unfortunately none of these studies reported a clear financial benefit for using the proposed navigation systems. With regard to evaluating cost-effectiveness of AR systems, the only evaluation identified was that of the RIO augmented haptic surgery system (Swank et al. 2009). While this system was shown to be cost effective, the analysis also showed an increased number of patients undergoing the procedure, possibly attracted by the novelty of the technology.

Thus, successfully transitioning from a laboratory implementation and testing to clinical care now becomes not only a matter of providing improved healthcare, but also of being cost effective. If the intent is to develop systems that will be clinically adopted, then cost should also be considered during the research phase and not ignored until the clinical implementation phase,

which seems to be the case for most recently developed systems that have experienced low traction in terms of their clinical translation.

5 Future perspectives

In the research setting, focus has shifted towards modeling and accommodating for soft tissue motion and deformation, and in some cases developing systems that attempt to side step this challenge. Keeping in mind that the overall goal of this domain is to provide improved patient care and not develop algorithms and systems for their mathematical beauty and novelty, side stepping an issue may sometimes be the correct choice. Though, further research into motion and deformation modelling is merited.

A subject that has not been sufficiently addressed by researchers developing image-guided navigation and AR systems is the design of optimal human computer interfaces, currently only addressed from the information display perspective. Researchers have objectively designed display methods for neurosurgical procedures (Kersten-Oertel, Chen, and Collins 2014), and for interventional radiology procedures (Varga, Pattynama, and Freudenthal 2013), but in most cases display choice is arbitrary. In addition, the conclusion that that overwhelming the operator with complex available information is actually detrimental has stimulated workflow analysis and investigation of context aware systems, focused on displaying the right amount of information when it is actually needed. Unfortunately, the operator's interaction with the system is often very cumbersome, with the system being controlled by proxy – the system developer performing the interaction based on the clinician's requests. A plausible explanation for this approach is the lack of intuitive system control by others besides the developers. Extreme cases described in (Grätzel et al. 2004) reveal that clinical staff required close to seven minutes to execute a desired selection which only consisted of a mouse click. This aspect of system design requires further efforts on the part of the research community.

Finally, the cost aspect of novel systems should influence the design of future AR systems. Costly novel solutions will most often not be widely adopted. If the choice is between using a costly imaging modality, e.g. intra-operative MR, in combination with simple algorithms, as opposed to a cost effective imaging modality, e.g. 3D US, in combination with complex algorithms, the later has higher chances of widespread adoption.

Transitioning from the laboratory to the commercial domain remains a challenge, as illustrated by the ratio of commercial systems to laboratory prototypes presented here. On the other hand, medicine is one of the domains where AR systems have made inroads, overcoming both technical and regulatory challenges which are not faced in other application domains. Given the active research in medical AR and the large number of laboratory systems, we expect to see additional AR systems or systems incorporating elements of AR in commercial products. While we use the term medical augmented reality to describe the domain, in practice the important aspect of these systems is that they augment the physician's abilities to carry out complex procedures in a minimally invasive manner, improving the quality of healthcare for all of us.

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