In-Situ Visualization of Medical Images Using Holographic Optics

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Abstract. We present the first autostereoscopic visualization system to project a real-time (live) medical data slice in-situ by use of a holographic optical element. Our system can project an essentially (1 mm in-slice accuracy) viewpoint-independent real-time virtual image into its actual anatomic location, enabling natural hand-eye coordination to guide invasive procedures. Our system does not require tracking or a head-mounted device, and it can project a 104x112 mm virtual image from a much smaller 19.3x15.5 mm source image. The system's optics are non-axial, arranged so that the source image does not block the direct view of the patient and allows sufficient room for long tools to operate on the patient. We are currently adapting this system for use with ultrasound for guiding liver biopsy and amniocentesis.

1 Introduction

In the current practice of medicine, images are routinely acquired by ultrasound, computerized tomography (CT), magnetic resonance imaging (MRI) and other modalities. These images are viewed on a film or screen, rather than by looking directly into the patient. This separation between image display and the patient workspace requires a clinician using the images for real-time guidance to mentally integrate two disparate frames of reference. The difficultly in performing such mental integration is problematic for performing invasive procedures, where direct physical interaction with the region being imaged is required. Examples of such procedures include vascular access, biopsy, amniocentesis, and minimally invasive (keyhole) surgery.

A number of researchers have worked to develop more natural ways to merge images with the perceptual real world, thereby removing the clinician's need to shift their gaze between the patient and the image [1–6]. These techniques fall into the broad category of *augmented reality* (AR), which enhances what is predominantly a real scene with virtual objects. For example, in the case of guiding needle biopsy, both the patient and needle are real. The "virtual" addition to the scene may consist of a real-time ultrasound image being used to guide the biopsy procedure or an MR or CT image acquired previously. AR seeks to project such images *in situ* (in the location from which they were scanned).

The most common method for displaying an in-situ object in current commercial and research AR systems is to present a separate viewpoint-dependent rendering to each eye, such that stereoscopic vision may determine depth [1–3]. Doing so requires both real-time computation to generate an appropriate rendering for each eye, as well as some sort of tracking to determine each eye's 3D position. Many such systems make use of either a head-mounted display (HMD) or special, e.g. polarized, glasses. All of these systems have a number of difficulties, some of which are technical hurdles but others of which are intrinsic, such as conflicting depth cues (e.g. accommodation and convergence) [7].

Optical systems that generate in-situ images without tracking or a head-mounted display offer a solution to many of these difficulties. The perceived 3D location of each in-situ point in these systems is essentially independent of viewpoint, allowing natural depth perception of the 3D scene. Accordingly, these systems are *autostereoscopic* [8]. Such systems may either project a *holographic image* or they may project a true optical virtual image, in the latter case either by means of a semi-transparent mirror or, as presented here, by means of a *holographic optical element* (HOE). In contrast to a holographic image, an HOE is a hologram of an optical system that produces the desired image projection (see Section 2).

1.1 Holograms for AR

Holographic images are naturally autostereoscopic and well-suited for interventional guidance. Significantly, they can be merged with a direct view of the patient, allowing the clinician to see both the in-situ holographic image as well as where they are puncturing the skin. Such merger of direct vision with in-situ visualization is achievable by use of a narrow band hologram, which allows the bulk of the visible spectrum to pass directly through unmodified.

Significant research has been done in the area of real-time projection of 3D holographic images. A recent break-through has been the development of a rewriteable holographic recording medium by Tay, et al. [9]. Their new photorefractive polymer composite changes its refractive index in response to the recording laser via an electrical rather than chemical process, allowing the creation of a hologram that can be repeatedly erased and re-recorded. Their process is currently slow, requiring approximately 2 minutes to record an image, but future advances could potentially allow a sufficiently powerful laser to record holograms at video frame rates. Even if such a feat were to be achieved, however, there is a remaining group of problems for using holographic images in augmented reality medical applications.

1.2 Difficulties Utilizing Holographic Images for AR

The preferred method of creating a holographic image from an acquired medical image is to compute the appropriate phase patterns for each location on the hologram (hogel) directly from a computer model, and then individually write each hogel (utilizing a spatial light modulator) as described in [9]. There are two potential hurdles to this approach. First, the resulting tessellation of the hologram into small hogels (each of which records only one 2D perspective of the 3D object to be displayed) quantizes the desired parallax effects and stereoscopic depth perception. Second, it can be time consuming both to compute the plethora of perspectives and to individually (i.e., sequentially) write the large number of hogels to the hologram media.

The second challenge can sometimes be mitigated by only computing and recording perspectives across the horizontal axis [9]. Even when such a hologram is properly aligned with the viewer, vertical changes in viewpoint will lead to different perceived locations for the hologram image along the vertical axis. This may be acceptable for "Princess Leia" floating in space, but could be disastrous if used to guide an invasive procedure. Invasive procedure guidance requires accurate localization along all three axes, as clinicians may well tilt their heads or move them vertically as they bend over a patient in the normal course of performing an intervention.

Taking these hurdles together, it becomes apparent that for the foreseeable future *hologram recording is unamenable to real-time updating* to match ongoing operational scans, e.g. from ultrasound. The time required to update a 2D hogel array will also preclude holographic video of pre-acquired periodic time sequences of images, e.g. cardiac gated volumetric CT. Furthermore, even if these hurdles are overcome, future lasers suitable for real-time hologram writing will likely be large and high-powered, making it difficult to construct a safe hand-held system that does not block the operator's vision or place physical equipment in the way of surgical tools.

1.3 Other Autostereoscopic In-Situ Visualization Methods

An alternative approach is to project a true optical virtual image, which occurs as the result of the *apparent* in-focus convergence of light rays, such as a reflection in a mirror or the magnified image produced by a magnifying glass. *Like holographic images, true optical virtual images are naturally autostereoscopic.* This approach is capable of autostereoscopic real-time operation using current technology. Real-time tomographic reflection (RTTR), such as is employed by Stetten's sonic flashlight, is one such AR technique [4–6]. As shown in Fig. 1, RTTR utilizes a half-silvered (semi-transparent) mirror to project an in-situ virtual image from a real-time image source (such as an LCD or OLED display). By rigidly connecting the autostereoscopic visualization device to the scanning device, the need for cumbersome tracking equipment is altogether avoided.

Until recently, RTTR was the only technique available for projecting in-situ autostereoscopic virtual images in real time. Unlike holography, however, RTTR is typically restricted to displaying a 2D manifold (albeit corectly located and perceived in 3D space) of the same size, shape, and mirrored position as the display source. Accordingly, it can be difficult or impossible to construct a hand-held RTTR system that is not unwieldy but is still capable of guiding deeper procedures such as liver biopsy or amniocentesis. A hand-held form factor is especially desirable for use with portable scanning technologies, such as ultrasound.

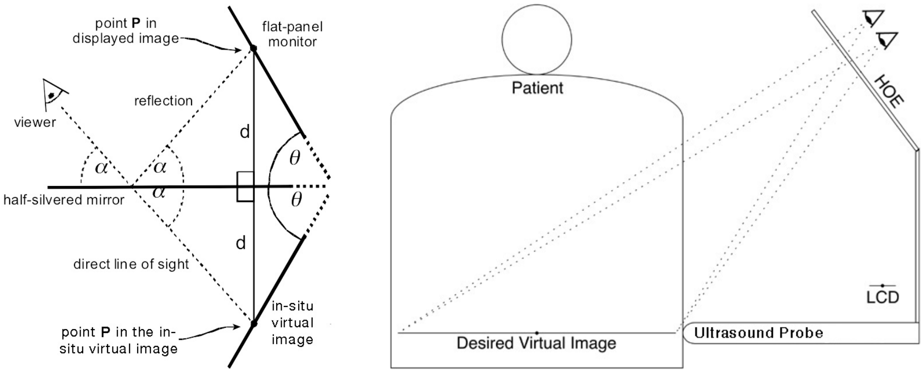

Fig. 1. Left: RTTR Configuration: A half-silvered mirror bisects the angle between the in-situ virtual image (coincident with the scanned data, e.g. ultrasound slice, within the patient) and the flat-panel monitor. Point P in the virtual image and its corresponding location on the monitor are equidistant from the mirror along a line perpendicular to the mirror (distance = d). Because the angle of incidence equals the angle of reflection (angle = α) the viewer (shown as an eye) sees each point in the reflection precisely at its corresponding physical 3D location, independent of viewer location. **Right:** An HOE can be used to project an autostereoscopic virtual image whose size, shape, and position need not be identical to that of the display source.

2 Holographic Optical Elements

There is a need for an AR method that is not only *presently* capable of real-time, in-situ autostereoscopic visualization of "large" objects, but is also capable of doing so from a hand-held device without using head tracking, blocking the operator's vision, or placing physical equipment in the way of surgical tools. Holography is not yet capable of real-time operation, and it will not be implementable in a hand-held form factor for the foreseeable future. RTTR has already been embodied in a real-time hand-held device (the sonic flashlight), but is capable of visualizing only 2D manifolds of limited size without resorting to an unwieldy form factor and/or blocking physical access to the patient by placing a mirror in the way of surgical tools. Here we present an alternative approach, originally proposed (but unimplemented) in [10].

An HOE can be used in lieu of RTTR's semi-transparent mirror, potentially allowing the creation of a hand-held device with the above capabilities. This is possible because a single narrow-band HOE can appear transparent, and yet still combine the magnifying capabilities of a lens with the "repositioning" capabilities of a diffraction grating to project a large in-situ true optical virtual image. The content of the virtual image is generated from a semi-arbitrarily positioned small real-time image source, such as an LCD back-light by a laser. Thus, an HOE is capable of enabling a device such as depicted on the right in Fig. 1.

An HOE can be conceptualized as a permanently recorded hologram, whose purpose is not to project a fixed 3D image, but rather to act as an optical element, such as a lens or a prism. In the present case, the purpose of the HOE is to project an autostereoscopic virtual image containing the data displayed on a separate real-time image source. Real-time operation is achievable because the image source, not the HOE, is updated in real time to visualize each new image "frame." The visualization of larger objects by way of an uncumbersome hand-held device is possible due to the HOE's diffraction-based operation and lack of reliance on a large, high-quality laser. Finally, an unobstructed view of the patient is possible through the HOE if the HOE is sufficiently narrow-band.

As with RTTR, the use of a 2D image source unfortunately restricts an HOE-based system such that, at any given moment, it can only visualize data lying on a 2D manifold. The projected tomographic data can be correctly located and perceived in 3D space, and different manifolds of data may be examined in temporal sequence by physically moving the device (and thus the location of the in-situ visualization). However, simultaneous visualization of a 3D volume is not possible without, at minimum, the use of multiple optical elements and a high-speed image source to automatically project a temporal and spatial series of virtual image "slices" at known locations and in rapid succession. Even so, present technology is either at or near the capability required to project a stack of virtual images in real time, and so HOE design (as opposed to holography improvements) may well usher in the era of 3D real-time autostereoscopic visualization.

Even without volumetric 3D displays, HOE-based autostereoscopic visualization systems may soon be capable of guiding deeper procedures such as liver biopsy or amniocentesis by projecting real-time 2D ultrasound in situ, and future HOE-based 3D visualization systems may be capable of visualizing arbitrary volumetric data in real time, such as may be acquired by 3D ultrasound, OCT, or even preoperative MRI or CT registered in real-time to ultrasound, etc. Not only would these new visualization capabilities have the potential to improve the quality of care for existing procedures, but new interventional procedures may also be enabled, such as out-of-plane needle insertion to reach problematically located targets.

3 Method

There are several types of HOE, each with a different fabrication method. Regrettably, no HOE is capable of projecting a perfect virtual image; there will always be some degree of optical aberration that results in blur. Optical aberrations are inherent to any non-trivial optical component[3], whether refractive such as a lens or diffractive such as an HOE. Unfortunately, blur in a virtual image degrades its autostereoscopic quality, because a projected point that is classically blurred over the entire aperture of an HOE will be perceived as being in different

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[3] A perfectly flat front-surface mirror can be aberration-free.

locations when viewed through different regions of the HOE. Accordingly, one of the major goals in designing an HOE-based in-situ visualization system is the minimization of blur, not only to produce images that appear sharp, but also to reduce the undesired dependence of apparent target location upon viewpoint.

In general, an HOE-based system is designed using optical simulation and optimization software (in particular, we have made use of the commercial Zemax EE optical engineering program). The HOE's phase function, which fully describes, e.g., the refractive index across the HOE's surface, is usually jointly optimized with the remainder of the device's optical components, including their physical layout. Such optimization is guided by an often-complex merit function, designed to favor physically realizable designs while minimizing optical aberrations. Due to their complexity, merit functions are typically subject to many local minima. Accordingly, such optical design is both an art and a science, requiring a carefully crafted merit function and tedious coaxing of the system through the solution space by means of many carefully chosen intermediate designs (and corresponding merit functions).

A complete HOE-based visualization system requires, at minimum, an HOE and a display source, such as an LCD. Each pixel of the display source must emanate diffused light at the HOE's operating wavelength, which may be accomplished by use of an expanded laser beam for illumination paired with an optical diffuser. In order to help correct for the HOE's optical aberrations, it may be necessary to place additional corrective optics between the image source and the HOE. To avoid either blocking the operator's vision or placing physical equipment in the way of surgical tools, such corrective optics must themselves be kept out of the way. The properties of these corrective optics are jointly optimized with the rest of the optical system. The set of corrective optics may include a fiber optic faceplate located adjacent to the display source. The fiber optic faceplate can serve dual purposes, correcting field curvature aberration while simultaneously functioning as the afore-mentioned optical diffuser.

4 Results

We have designed and constructed one such HOE-based system (see Fig. 2), capable of projecting a virtual image sized 104 mm wide by 112 mm tall, 5.4 times wider and 7.2 times taller than our 19.3x15.5 mm image source. To simplify our initial design, we positioned the virtual image at 1 m from the HOE, further than likely to be used in clinical practice (reducing this distance increases optical aberrations). Our design has an unobstructed line of sight from the HOE to the virtual image, with the image source and two corrective lenses located off-axis, out of the way of the direct line of sight to the patient.

The projected virtual image is well focused, and thus objects in the virtual image do not appear to substantially change their position across the range of viewpoints. In particular, over a normal range of viewpoints, objects empirically do not appear to move by more than 1 mm within the image slice, as quantitatively measured using a digital camera on a precision positioning stage and

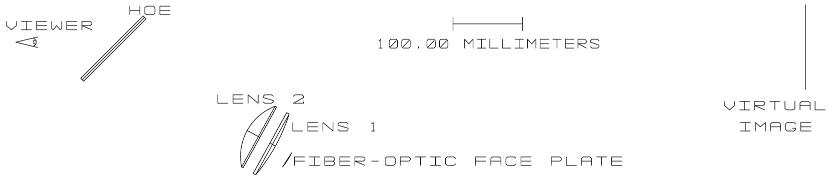

Fig. 2. The layout of our HOE-based autostereoscopic in-situ visualization system.

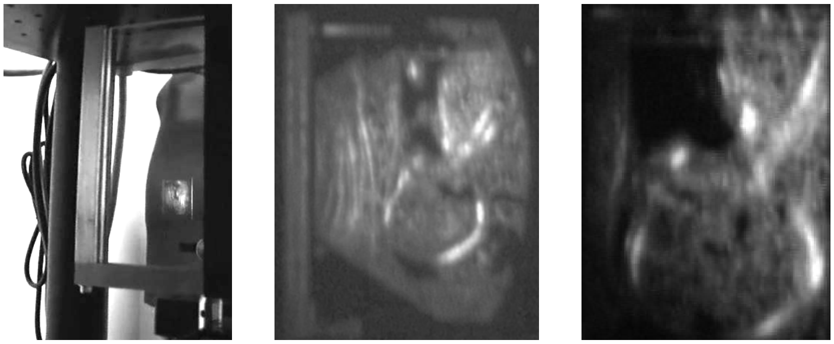

Fig. 3. Photos showing fetal ultrasound projected inside the mother. The images appear to have higher resolution in person, due primarily to the larger dynamic range and smaller pupil size of the human visual system. The left photograph shows the ultrasound image floating inside the mother, as viewed through the HOE. The other photographs are “zoomed in,” showing part of the fetus, oriented facing left with the head down. Some of these are still-shots from a video we recorded showing in-situ autostereoscopic visualization of fetal movement inside the mother. For this demonstration, we played back previously recorded ultrasound. However, by simply attaching an ultrasound machine to our current device we could project real-time ultrasound data in situ.

well in agreement with our optical simulation. Actual in-situ projection of fetal ultrasound is shown in Fig. 3.

5 Conclusion

In-situ guidance of deep procedures such as liver biopsy or amniocentesis requires the real-time projection of large virtual images of 2D (e.g., ultrasound) or 3D data in situ, without blocking the operator’s vision or placing physical equipment in the way of surgical tools.

We hypothesized that HOE-based autostereoscopic visualization systems are capable of meeting these requirements. Rather than seeking to project true 3D holographic images (and thus requiring real-time updates of a hologram), we use a permanently recorded HOE to project a real-time virtual image from a readily available image source such as an LCD (the LCD, not the HOE, is updated in real time). Unlike RTTR systems, the size, shape and position of the virtual image are not tightly constrained by the size, shape, and position of the image source. In the future, volumetric 3D visualization may also be possible.

We have designed, built, and tested the first such HOE-based AR system, successfully demonstrating the chief benefits of using an HOE.

Having shown that HOE-based in-situ guidance of deep procedures is possible, we are now working on a new design with a larger virtual image and a reduced distance between the HOE and the virtual image, which are more desirable for hand-held in-situ projection of ultrasound. Our new optical design is more challenging, because the increased image size and reduced optical distance exacerbate many optical aberrations. Once our design is finished, however, our new autostereoscopic device should be well-suited for guiding deep invasive procedures.

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References

1. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B.: Recent advances in augmented reality. IEEE Computer Graphics and Applications **21**(6) (2001) 34–47
2. Fuchs, H., State, A., Pisano, E., Garret, W., Hirota, G., Livingston, M., Whitton, M., Pizer, S.: Towards performing ultrasound-guided needle biopsies from within a head-mounted display. In: Visualization in Biomedical Computing, Hamburg, Germany (1996) 591–600
3. State, A., Ackerman, J., Hirota, G., Lee, J., Fuchs, H.: Dynamic virtual convergence for video see-through head-mounted displays: Maintaining maximum stereo overlap throughout a close-range work space, New York City, International Symposium on Augmented Reality (ISAR) (2001)
4. Hofstein, S.: Ultrasound scope (April 1980) Patent 4200885, filed 2 Feb. 1978, granted 29 April 1980.
5. Masamune, K., Masutani, Y., Nakajima, S., Sakuma, I., Dohi, T., Iseki, H., Takakura, K.: Three-dimensional slice image overlay system with accurate depth perception for surgery. In: Medial Image Computing and Computer-Assisted Intervention (MICCAI). Volume 1935., Pittsburgh, Springer (2000) 395–402
6. Stetten, G.: System and method for location-merging of real-time tomographic slice images with human vision (July 2003) Patent 6599247, filed 11 Oct. 2000, granted 29 July 2003.
7. Drascic, D., Milgram, P.: Perceptual issues in augmented reality. In Fisher, S.S., Merrit, J.O., Bolas, M.T., eds.: Stereoscopic Displays and Virtual Reality Systems III. Volume 2653 of Proceedings of the SPIE., SPIE (1996) 123–124

8. Dodgson, N.A.: Autostereoscopic 3d displays. Computer **38**(8) (August 2005) 31–36
9. Tay, S., Blanche, P.A., Voorakaranam, R., Tunc, A.V., Lin, W., Rokutanda, S., Gu, T., Flores, D., Wang, P., Li, G., St Hilaire, P., Thomas, J., Norwood, R.A., Yamamoto, M., Peyghambarian, N.: An updatable holographic three-dimensional display. Nature **451**(7179) (2008) 694–698
10. Nowatzyk, A., Shelton, D., Galeotti, J., Stetten, G.: Extending the sonic flashlight to real time tomographic holography (2004) Workshop AMI-ARCS 2004, held in conjunction with MICCAI 2004 September 30th, 2004, Rennes (France). Published online at http://ami2004.loria.fr/.