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Appl Opt. Author manuscript; available in PMC 2015 June 22.

Published in final edited form as:
Appl Opt. 2014 August 20; 53(24): 5421–5424.

Refocusing a scanned laser projector for small and bright images: Simultaneously controlling the profile of the laser beam and the boundary of the image

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Abstract

This paper describes a projection system for augmenting a scanned laser projector to create very small, very bright images for use in a microsurgical augmented reality system. Normal optical design approaches are insufficient because the laser beam profile differs optically from the aggregate image. We propose a novel arrangement of two lens groups working together to simultaneously adjust both the laser beam of the projector (individual pixels) and the spatial envelope containing them (the entire image) to the desired sizes. The present work models such a system using paraxial beam equations and ideal lenses to demonstrate that there is an "in focus" range, or depth of field, defined by the intersection of the resulting beam waist radius curve and the ideal pixel radius for a given image size. Images within this depth of field are in focus and can be adjusted to the desired size by manipulating the lenses.

1. Introduction

Our ultimate goal is to create a projection system suitable for use under magnification. Our particular application for this is the injection of virtual images under the objective lens of a stereo microscope, for guidance during eye surgery using Optical Coherence Tomography (OCT) images of structures in the anterior portion of the eye acquired in real time. The use of a virtual image permits its placement at its correct location within the actual tissue in the surgical field, superimposed on the normal view through the stereo microscope. We have designed a system, shown in Figure 1, that uses a half-silvered mirror to insert a virtual image into the optical path of the microscope so that it appears at a defined location in space (i.e. not at infinity) [1, 2].

Augmented reality systems such as ours are often used in surgical settings. Augmented reality refers to the integration of virtual objects with the real world, as opposed to virtual reality, which creates and entirely synthetic environment [3]. These virtual objects can be targets for the surgeon, or can represent relevant information taken from medical imaging, done either before or during the procedure.

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The implementation of the augmented reality system depends on how the surgeon is interacting with the surgical field. In open surgeries where there is no intervening imaging system, the virtual object is a translucent image placed between the surgical field and the surgeon. Head mounted displays (HMDs) create the image on the screen mounted in front of the operator's eyes, and are capable of producing stereoscopic images [3]. Projection based displays use a projector to create an image on the surface of the surgical field [4]. During laparoscopic surgeries, the field is viewed through a camera in the scope, and so virtual objects are introduced into the video stream that is viewed by the surgeon [5,6].

Augmented reality systems for microsurgery can introduce virtual objects through the microscope, most readily as a translucent overlay that is injected into the system after the objective lens [7, 8]. The RESCAN system in [8] provides OCT images through a heads-up display integrated into the oculars of the microscope. However, these images are “at infinity”, and are therefore flat and always in focus, and therefore cannot give a sense of depth or 3D shape. They are also not aligned with the underlying anatomy. Our system integrates intraoperative OCT images in a way that differs from the state of the art system in [8] by the use of the in situ *optical* virtual image which exists at a defined depth and location, and is inserted into the optical path of the microscope *before the objective lens.* The virtual image could also be manipulated with adaptive optics to produce curved 3d surfaces.

In our particular application, we require a narrow bandwidth light source to allow the projection system to be used with subsequent diffractive optics. We also require very small and very bright pixels. Small pixels are necessary to maintain image resolution after magnification. Bright pixels are necessary to withstand the light dilution caused by magnification. Laser based projection systems have the ability to fulfill all three requirements. Laser beams can be focused to very small, very bright spots, and in most cases they have relatively narrow bandwidth (often practically monochromatic). However, commercially available laser based projection systems are typically designed for creating images viewable at much larger sizes than appropriate for magnification (i.e. pocket projectors for giving presentations and watching videos), and thus some modification is required for them to project tiny images. This paper addresses the general issue of manipulating these types of laser projectors to control the width of both the individual laser beams (pixels) and the envelope that contains them (image). This problem is central to the design of a projection system suitable for our microsurgical augmented reality system.

2. Background

We examine the use of scanned laser projectors for the purpose stated above. As a typical reference point, we consider Microvision's PicoP projection system, which combines red, green, and blue Gaussian-beam lasers into a single beam that can produce a full range of colors, projecting an image on any surface (typically some sort of diffusing screen) by sweeping the laser beam in a sine wave raster pattern using a biaxial microelectromechanical systems (MEMS) mirror [9]. The combined laser beam is not fully collimated, as it must diverge slightly so that the pixels fill the image as the image expands (see Figure 2). In order to have the image and pixel sizes match at the manufacturer's target distances (0.5 m and further), the combined beam is internally focused to a waist at about 0.5 m in front of the

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projector [9]. After this point, the beam radius and desired pixel size are in good agreement, leading to the projector's “infinite focus” property, i.e., unlike traditional planar image source projectors it does not require focus adjustment. However, for very small image sizes (projected much closer to the projector than 0.5 m), the pixels are significantly oversized and overlapping, causing the image to blurred (Figure 2). Therefore, to get a small image from the projector, we cannot simply place a diffusing screen at such a close range.

3. Methods

Single Lens Focusing

As we will show, for our desired range of pixel sizes (0.01 to 0.1 mm pixel radius) an “in focus” image cannot be produced by combining such a projector with a single lens. By “in focus” we mean an image in which the actual pixel size is not larger than the pixel spacing. A single lens will focus the laser beam to a waist near the back focal plane, but since the image cone is diverging entering the lens, it converges more slowly exiting the lens, forming a diffraction-limited spot past the back focal plane. (In comparison, a collimated image entering the lens will be condensed to a diffraction-limited spot at the back focal plane.) Increasing lens power to converge the image closer to the lens will, of course, also move the beam waist even closer to the lens, and so the image can never focus coincident with the beam waist (see Fig. 3). The light from the projector effectively behaves as two separate but simultaneous image systems, defined as follows: (1) The image cone is the envelope containing all of the light within the image. The width of the image cone at a given location along the optical axis determines the image size and the *desired* pixel size. The cone and the desired pixel size behave according to geometric (not Gaussian beam) optics. (2) The laser beam's profile behaves according to Gaussian beam optics, and the actual pixel size is determined by the radius of the laser beam at a given location along the optical axis.

Multiple Lens Focusing

In order to simultaneously control the location of the laser beam's waist and adjust the image cone to the desired size, we need more degrees of freedom to independently control the two systems. We have developed what we believe to be a novel application of a two-lens system to resize the image (see Fig. 4). The first lens is selected and aligned to collimate the image cone. This also focuses the laser beam to a waist slightly past the back focal plane. The beam divergence is greatly increased, so while the image remains the same size along the collimated region, it becomes increasingly blurred as the pixels become larger. A second lens is then placed to refocus the laser beam and resize the image cone. The image cone is focused to a spot at the back focal plane of the second lens, while the laser beam is focused to a waist past the focal plane, near the desired image plane. As the distance between the two lenses increases, the waist approaches the back focal plane.

The third and final element of the system is the translucent diffusing screen, which is placed so as to create the in-focus image after the second lens. The distance between the second lens and the diffusing screen determines the intersection with the image cone, and thus the overall image size. Placing the diffusing screen closer to the back focal plane of the lens will, of course, produce a smaller image.

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To quantify the behavior of the system with different lens arrangements, we modeled the behavior of the laser beam using Self's equations for beam propagation, which assume paraxial conditions [10]. Without loss of generality, the focal lengths of the first and second lenses are set at 30 mm and 40 mm, respectively, a physically realizable setup suitable for our purposes. The location of the new beam waist after each lens is given by

$$\frac{1}{S+\frac{Z_R^2}{s-f}}+\frac{1}{S'}=\frac{1}{f} \quad (1)$$

where s is the distance from the lens to the input waist, f is the focal length of the lens, s' is the distance from the lens to the output waist, and Z_R is the Rayleigh range of the input beam. Using Self's equations, it is straightforward to determine the waist size of the output beam and the output Rayleigh range [10]. The behavior of the image cone was modeled using geometric optical properties. The angle of the cone after the second lens is determined from the equivalent focal length (EFL) of the lens and the size of the cone entering the lens. This angle determines the size of the cone after the focal point. The ideal pixel size is the appropriate fraction of the cone size, as determined by the pixel-count of the projector. Figure 4 shows how the pixel size and in-focus image location vary with the distance between the two lenses (90-240 mm).

As the distance between the two lenses increases (increasing the beam size entering the second lens), the resulting beam-waist radius decreases, and the beam waist moves closer to the back focal point of the second lens. The solid black line in Figure 5 shows the “ideal” pixel size that corresponds with the image cone size at that location. The intersection between this line and a particular beam radius curve shows ranges at which the final image is in focus for the corresponding distance between the two lenses. The beam waist curve intersects the ideal pixel line in two places. The space between the intersection points of the beam radius curve and the pixel size line defines the depth of field over which the image will be in focus. Pixels that are somewhat smaller than the ideal pixel size would not typically cause a significant problem, since the blurring of subsequent optics, or even just the human eye, is likely to cause the spaces between pixels to be imperceptible. This depth of field decreases rapidly as the inter-lens distance increases and the beam waist radius decreases. Depth of field over all image sizes could be improved by increasing the focal length of the second lens, but doing so requires a larger diameter lens placed further away from the projector.

4. Conclusion

We have presented a novel projection system for small, bright, potentially monochromatic images, using a scanned laser projector as the source. Our system addresses the issue of simultaneously controlling both the laser beams and the envelope containing them. Single lens systems can be constructed to control either one of these components, but not both with a single setup. Our proposed system uses two lens groups specially arranged to partially decouple the system's effects on these two components, focusing both the image and the individual pixels to their desired sizes. This produces a very small, very bright image that can be diffused and then further operated upon by either traditional or diffractive optics. The

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successful resizing of the images from a scanned laser projector fulfills our requirement for an image projection system usable under magnification. Furthermore, we have shown that this type of manipulation of sets of laser beams is possible with a relatively simple system. These findings are essential for our continued work on the microsurgical augmented reality system we are presently developing.

Acknowledgements

This work was funded in part by NIH grants #R01EY021641 and #R21-EB007721, and a grant from Research to Prevent Blindness. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. (0946825).

References

1. Galeotti J, Sajjad A, Wang B, Kagemann L, Shukla G, Siegel M, Wu B, Klatzky R, Wollstein G, Schuman J, Stetten G. The OCT penlight: In-situ image guidance for microsurgery. Proc. SPIE. 2010; 7625:762501.
2. Stetten, G. System and Method for Location-Merging of Real-Time Tomographic Slice Images with Human Vision. U.S. Patent no. 6,599,247, submitted Oct. 11, 2000, issued, July 29, 2003
3. Van Krevelen DWF, Poelman R. A survey of augmented reality technologies, applications and limitations. International Journal of Virtual Reality. 2010; 9:1–20.
4. Wen R, L Tay W, Nguyen BP, Chng CB, Chui CK. Hand gesture guided robot-assisted surgery based on a direct augmented reality interface. Computer methods and programs in biomedicine. 2014; 116:68–80. [PubMed: 24438993]
5. Kang X, Azizian M, Wilson E, Wu K, Martin AD, Kane TD, Peters CA, Cleary K, Shekhar R. Stereoscopic augmented reality for laparoscopic surgery. Surgical endoscopy. 2014; 28:2227–2235. [PubMed: 24488352]
6. Volonté F, Buchs NC, Pugin F, Spaltenstein J, Schiltz B, Jung M, Hagen M, Ratib O, Morel P. Augmented reality to the rescue of the minimally invasive surgeon. The usefulness of the interposition of stereoscopic images in the Da Vinci™ robotic console. The International Journal of Medical Robotics and Computer Assisted Surgery. 2013; 9:e34–e38.
7. Becker, BC.; MacLachlan, RA.; Hager, GD.; Riviere, CN. Handheld micromanipulation with vision-based virtual fixtures. Proceedings of IEEE International Conference on Robotics and Automation (ICRA); IEEE; 2011. p. 4127-4132.
8. Ehlers JP, Kaiser PK, Srivastava SK. Intraoperative optical coherence tomography using the RESCAN 700: preliminary results from the DISCOVER study. British Journal of Ophthalmology. 2014; 0:1–4.
9. Freeman M, Champion M, Madhavan S. Scanned Laser Pico-Projectors: Seeing the Big Picture (with a Small Device). Opt. Photon. News. 2009; 20:28–34.
10. Self SA. Focusing of spherical Gaussian Beams. Applied Optics. 1983; 22(5):658–661. [PubMed: 18195851]

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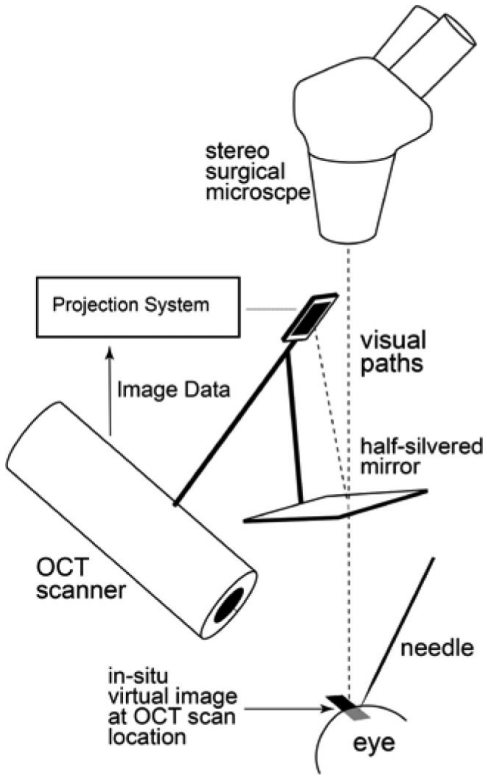

Figure 1.
Diagram of the OCT in situ imaging system. Adpated from [1].

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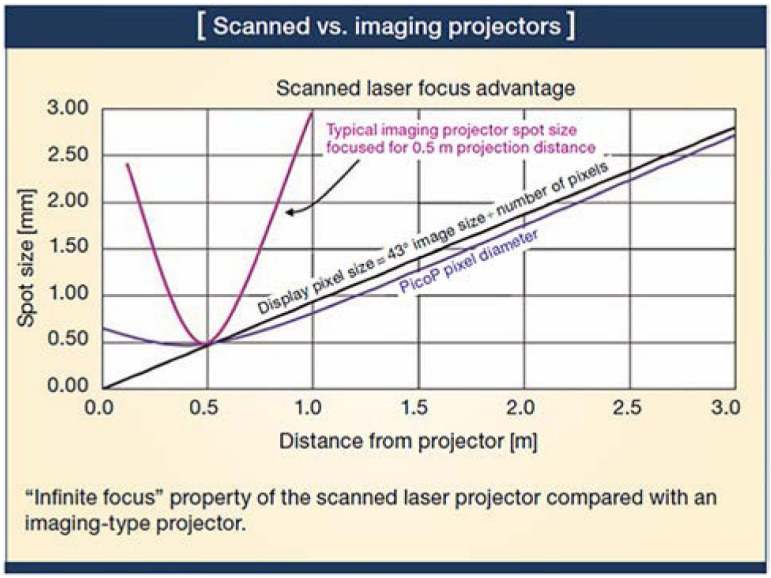

Figure 2.

Pixel size vs. distance from projector for the Microvision PicoP projector. Reprinted with permission [9].

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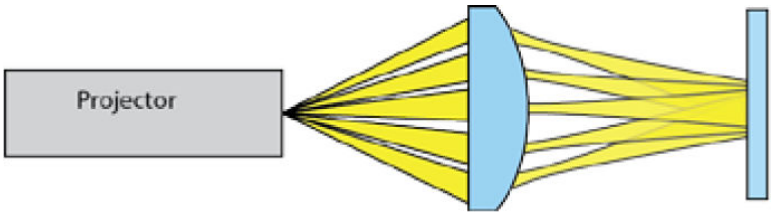

Figure 3.

Attempting to focus a laser-based projection system with a single lens. The projection screen and lens are positioned to project a small image, but the laser waist is unavoidably nearer to the lens, resulting in large and overlapping laser beams (i.e., pixels) on the projection screen.

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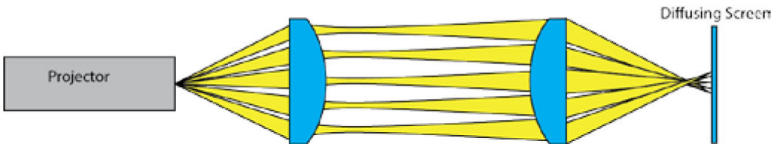

Figure 4.
Our two-lens system

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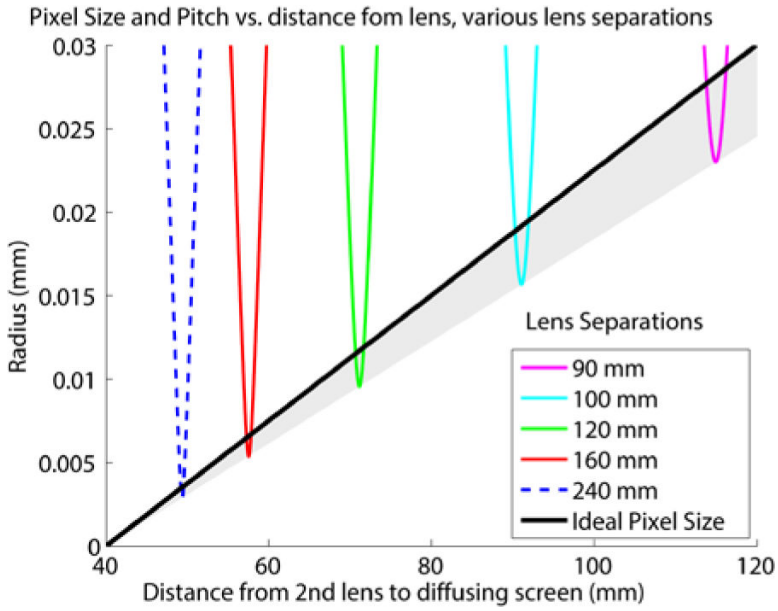

Figure 5.

Compare to Figure 2. Each inter-lens distance will result in a different beam profile. Only the portion of a profile that falls beneath the diagonal (indicated in gray) will result in non-overlapping "focused" pixels, determining the acceptable range of image distances (and thus image sizes) for that lens arrangement. Smaller separations between the lenses correspond to larger beam waists further from the back focal point, and larger depth of field.