Static Volumetric Three-Dimensional Display

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***Abstract*—We present here the development of a volumetric display based on the two-frequency, two-step upconversion technique using novel techniques for addressing the imaging volume. Two 1024×768 digital micromirror displays, driven by 30-W lasers at 1532 and 850 nm are utilized to generate fast scanning of the image volume in a 17 mm×17 mm×60 mm 2% erbium-doped lithium yttrium fluoride (YLF) crystal. Experimentally, images at 532 nm were created at 30 (frames)×1024×768 resolution, resulting in almost 23 million voxels, at 500 frames/s, significantly higher than that obtained with three-dimensional (3D) raster scanning (frame is 2D cross-sectional plane of the 3D image). Imaging optics modified from projector systems and fiber-optically coupled to the source, combined with custom designed software for converting two-dimensional (2D) rendering of volumetric images into control signals for the digital micromirror displays allow single-color image generation with no flicker and natural depth cues. Improvements in optical power efficiency and the speed of digital micromirror display controller boards are needed for the system to reach its full potential. The resulting system has the potential to increase resolution to nearly 800 million voxels without viewpoint obstruction and expand to three-color imagery.**

***Index Terms*—Three-dimensional (3D) displays, 3D, volumetric, digital micro-mirror device, crystal, TFTS, upconversion.**

I. INTRODUCTION

DESPITE the fact that the human visual system is uniquely constructed to function in a three-dimensional (3D) world, the majority of current commercially available display technologies are based on flat, two-dimensional (2D) methods of displaying visual information. In an attempt to display 3D information on these displays, many sophisticated and powerful techniques, such as perspective, shadowing, and texturing have been developed to trick the eye into seeing a 3D image [1]–[3]. These techniques, however, are ultimately limited in effectiveness because they do not provide depth cues in a manner that is natural to visual processing. Therefore, displays capable of producing a true 3D image are required to overcome the limitations of 2D displays. Only recent technological advances have allowed the creation of true 3D displays.

We present here the development of a volumetric display based on the two-frequency, two-step (TFTS) upconversion technique using novel techniques for addressing the imaging volume. Two digital micromirror displays (DMDs) are utilized to realize fast scanning of the image volume at high resolution without the time constraints and control issues involved with 3D raster scanning. Appropriately designed imaging optics, custom designed software for converting 2D rendering of volumetric images into control signals for the DMDs, and proper selection of infrared laser sources allow efficient, single-color image generation with a large viewing zone with no flicker and natural depth cues. The resulting system has the potential to increase resolution to nearly 800 million voxels and expand to three-color imagery.

II. BACKGROUND AND RELATED WORK

Of the many and varied methods used for generating 3D displays [3]–[5], our display is based on the two-frequency two-step (TFTS) upconversion technique [6], [7]. The basic idea of this technique is shown in Fig. 1. Photons from two infrared optical sources of different wavelength are incident on an optically active material and are absorbed by the material. The photon from the first source (what we'll refer to as the addressing source or laser) with wavelength λ_0 is absorbed by an atom, molecule, or ion in the ground state (E_0) of the material, thereby exciting the ion or molecule to an intermediate energy level (E_1), where it can stay with a nominal lifetime of τ_1. If a photon from the second source (what we will refer to as the imaging source or laser) with wavelength λ_1 arrives while the ion or molecule is in the E_1 state, then the energy is absorbed from the photon and the ion or molecule is excited into a higher state E_2. For a properly selected material, the next action is the radiation of the total absorbed energy, minus internal losses, as the ion or molecule returns to the ground state, generating a visible photon and hence a spot of light within the volume of the material. An image is created by addressing multiple volume pixels (voxels) to draw the larger image through the volume of the material. As the light emitted from each voxel disappears quickly after removing the addressing source, the entire picture must be refreshed at a sufficient rate to deceive the eye into seeing a single cohesive image without flicker, which requires a refresh rate of 30 to 100 Hz [1], [6]. In all systems, including the one presented here, a specially coated dome is placed over the imaging crystal to block any residual infrared light from the writing lasers in order to protect the viewer.

While the TFTS upconversion technique is used in a number of volumetric displays under development, there exist significant differences in the implementation of the display, one of which is the choice of host materials [8]. Both gaseous and solid host materials have been proposed and demonstrated for use in volumetric displays. The most practical gas-based system was realized by Kim and colleagues [9] using TFTS upconversion in rubidium vapor. The problems with gaseous hosts is the need to contain the material at high pressures in vessels that have opaque components, strongly limiting the field of view and the range of applications for which it is appropriate. Solid hosts are usually crystals or rare earth-doped heavy metal fluoride or ZBLAN

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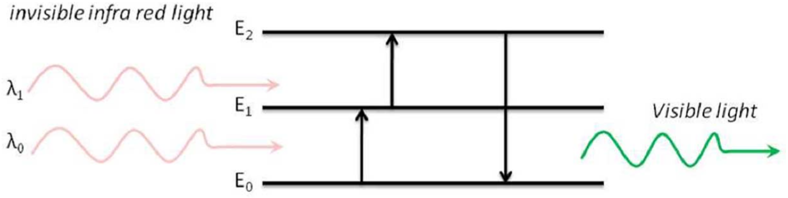

Fig. 1. Depiction of the TFTS process.

glass [1], [5], [10], although some polymer materials have been developed as well [11]. Different dopants can be used in the glass in conjunction with multiple imaging sources to generate light at red, green, and blue wavelengths, effectively creating three-color imagery. Since the crystals are usually clear, the viewing range is limited only by the scheme used to address the pixels and the physical positioning of the addressing and imaging sources and their corresponding optics. The advantages of using glasses over crystals are the ability to mold glasses into a variety of shapes to create unique displays and insensitivity to source polarization which simplifies the optical systems. The main limitation of crystal or glass-based displays in the past has been the small size of the materials, typically on the order of a few centimeters on each side of the volume. Larger crystal sizes have been realized by optically cementing several smaller pieces together, though with some loss of function [1].

The other significant difference in the realization of TFTS-based displays is the method used for addressing the large number of voxels needed to make a high resolution image. One such system utilizes arrays of lasers covered by focusing lens arrays located along two axes of the system [1]. An addressing array activates cross-sections of the crystal and then an imaging array shines light on only those parts of the cross-section needed to emit light and create the desired image. Successive cross-sections are addressed and imaged through the depth of the crystal to build the 3D image, and the process repeated at a sufficiently high refresh rate. While this method can significantly reduce the optical power required to activate each voxel, limitations arise on the resolution due to the limited size and density of laser arrays that can be reliably achieved, and the opto-electronic bandwidth.

Another method of addressing the arrays is a raster method [5], [12]–[14]. In this method, the beams from the addressing and imaging lasers are scanned through the crystal, one along the X-Y plane and one along the X-Z plane, in a manner similar to the addressing scheme of a 2D CRT or liquid crystal display. The scanning is most commonly performed by mechanical systems of mirrors, though acousto-optic cells have been used [12] and the use of micro-electro-mechanical systems (MEMS) can reduce the size of the system and the number of bulky moving parts required [13], [14]. An example of a MEMS device is the digital micro-mirror device (DMD) commonly employed in ubiquitous digital projection systems, which has been shown to be adaptable to 3D imaging. Sophisticated modeling and control software is readily available to drive raster based systems, independent of the final configuration or physical structure [5].

The primary drawback of the raster method is the need to address each voxel contributing to the image individually, which means the limits on the achievable complexity of the image are set by the speed of the scanning system. Consider, for example, the power and scan rate required to maintain a constant average power emitted by each voxel as the image volume increases. If a voxel emits an average power P_T under continuous excitation, then a voxel refreshed 30 times per second would require 30 times the excitation energy to emit the same average power. Now consider an N×N×N image containing N^3 voxels. In order to address every voxel in the image 30 times per second, the required scan rate, R_s would be $30 \times N^3$ Hz. The excitation time, τ_{ex} for each pixel would then be $1/\mathrm{R_s}$, and the excitation energy required would be N^3 times greater than that needed to address one pixel at a 30 Hz refresh rate [1]. For example, if $N = 100$, corresponding to one million voxels, then $R_s = 30$ MHz, $\tau_{\mathrm{ex}} = 33$ ns, and 100 000 times greater pump energy would be needed compared to that used for a single voxel. As the number of voxels in the image increase, one of two limiting conditions will occur. Either the high pump energy will exceed the damage threshold of the optical material or the scanning mechanism, whether mechanical or electrical, will reach its maximum speed. Images containing 100 million voxels, such as those obtained with a swept-screen display [8], would not be practical, nor would the higher resolutions targeted by the approach described in this work.

The approach used for our display takes advantage of significant advances in the technology surrounding DMDs and their driving systems. The approach allows planes of pixels to be addressed in parallel, greatly reducing the scanning speed required, and thus increasing the excitation time and decreasing the required pump energy. Returning to the previous example, assume now that the volume is divided into N planes, and that the $N \times N$ voxels in each plane are addressed simultaneously. To address each voxel 30 times per second, $R_s = 30 \times N$. For the $N = 100$ case computed previously, $R_s = 3$ kHz and $\tau_{\mathrm{ex}} = 333\,\mu$s. Each individual voxel, then, would need only 100 times more energy than that required by a single voxel at a 30 Hz refresh rate. Note that, since the voxels are addressed in parallel, the refresh rate is determined only by the number of planes used to render the image, not the number of voxels addressed in each plane. In practice, however, the power of the addressing lasers would still increase to ensure that sufficient energy is available to all pixels equally.

Another competing technology is based on holographic projection. While standard holographic methods require display pixel dimensions smaller than the wavelength of visible light, a virtual window approach proposed by See Real Technologies shows promise [15]. Pixel sizes of 50 μm square have been reported, which is comparable to the 16 μm pixels achieved with the system reported in this work. The use of parallel addressing of a computer-generated hologram and the use of a vir-

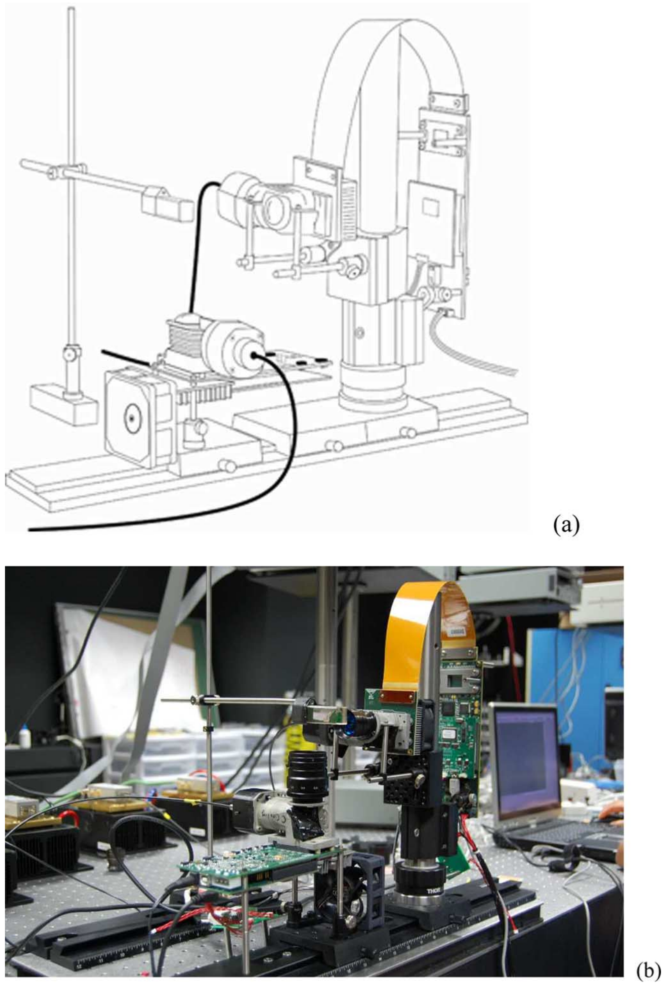

Fig. 2. (a) Picture of experimental setup. (b) schematic representation of the display components.

tual viewing window allow practical pixel sizes and refresh rates with good brightness.

Advances in the switching speed and the mirror density of current DMD devices permits massively parallel (1024×768) addressing of voxels at rates exceeding 30 000 frames/s. These parallel addressing schemes significantly increase the speed at which a glass imaging medium can be addressed and the resolution that can be achieved within each imaging plane. The increased speed can be used to address a greater number of image slices in the crystals already in use, effectively increasing the resolution, or can allow a larger imaging volume to be addressed without a loss of resolution.

III. SYSTEM OVERVIEW

The 3D display system we developed is depicted in Fig. 2. The small crystal in the center of the figure is the display volume. Below and to the right of the crystal are the opto-electronic systems that deliver the necessary optical signals to the crystal. Each system consists of optics to image a laser output onto a DMD, a DLP driver board to control the DMD, and optics to image the DMD output onto the desired area of the crystal volume. The DLP driver boards are connected to a PC that provides the necessary data and control signals for drawing the image in the crystal. The system on the bottom selects the vertical slice of the crystal in which the image is formed, and the system on the right activates those parts of the slice needed to create the desired image. The optical power comes from two high-power lasers (not shown) with independent temperature control to maintain stability throughout the operation of the display. The remainder of this section provides details of the system components.

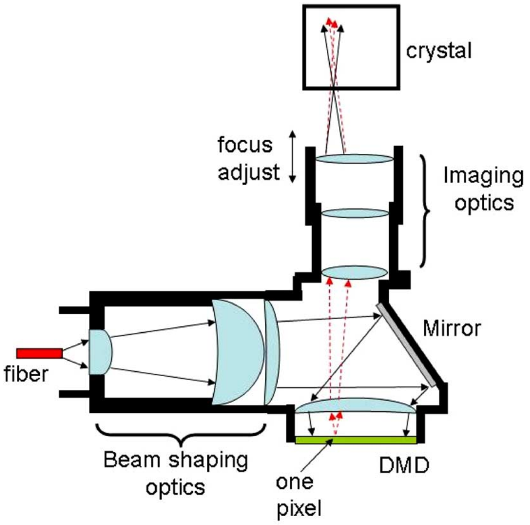

Fig. 3. Optical configuration for the projection system. Light emitted from the optical fiber is imaged onto the DMD through the beam shaping optics. The imaging optics project the light from each pixel onto the corresponding volume in the crystal.

A. *Optical Crystal*

The optical material used for the display is a 17 mm×17 mm×60 mm 2% erbium-doped lithium yttrium fluoride (YLF) crystal obtained. The crystal structure, details of which can be found in [16], allows for absorption of infrared light around 1532 nm and 850 nm. When light at both wavelengths is present, an electron in the ground state of the crystal undergoes two transitions resulting in a high energy state for the electron. When the electron transitions back to the ground state it releases energy in the form of photons at 532 nm (green). The high energy state lifetime is 25 ± 10 μs which allows (and requires) frequent refreshing or updating of the state of each voxel.

B. *DMD Projectors*

The DMD projection systems condition the laser light and steer it into the crystal with the high precision required to produce very-high resolution images. Each projection system starts with a lens system that collects light from an input optical fiber and spreads the power evenly over the full area of a DMD, as shown in Fig. 3. The optics are adapted from existing digital light projection systems to accommodate the change from incoherent white light to coherent, high power light in the infrared. The mirrors on the DMD are controlled by a digital light projection (DLP) controller board, and can be set to one of two states. In the “off” state, the mirror is set to reflect light away from the output port of the projection system, and thus no light will be directed to the crystal from the particular mirror.

In the “on” state, the mirror is set to direct light through the output port and onto the crystal. The DMDs currently in use, from the Discovery product line from Texas Instruments has a 1024×768 array of mirrors for the addressing laser and 1024×768 array of mirrors for the imaging laser, although larger DMDs could be used to increase the number of crystal slices obtainable. The output optics image the light from the DMD onto the crystal. Each set of optics provides the capability to adjust the depth of focus which allows the system to maintain a consistent voxel volume throughout the width and depth of the crystal.

C. DLP Boards and Driving Software

The DLP boards, manufactured by Texas Instruments Incorporated, used in our system are designed specifically for the DMDs used in the display. The base controller board is capable of 16 300 binary frames per second, with sequential or random row addressing possible. The board has a Xilinx Virtex 4 application field programmable gate array, 1 Gbyte of DDR2 SDRAM, and an 8 pin RJ-45 connector and 90-pin interface connectors for interfacing with the DMD and a programming computer.

The software used to provide data to the DLP boards, called CSPACE, was developed specifically for our system. CSPACE accepts 3D image data imported from other software such as 3DModeler and Blender and converts this data into a form readable to the DLP programs controlling the DMDs. For the purpose of shortening the development timeline and incorporating more advanced visualization features in the future, the visualization toolkit (VTK) from Kitware is used as the underlying layer for manipulating 3D graphics in CSPACE. VTK is used to perform different 3D graphics manipulation ranging from basic transformation to more advanced visualization features at the user front end (i.e., lighting, shading, clipping, etc.). CSPACE is capable of displaying 3D computer graphics model utilizing two DLP projection systems.

D. Laser Systems

Two high-power diode lasers coupled to multi-mode, large core fiber provide the optical input for the display. Each laser is a commercial-available, stabilized infrared source with a controller and integrated head block and a maximum optical power of 30 W. To maintain stable operation over long periods, each laser head block is mounted on a commercial thermo-electric cooler. The controller for the cooler allows stabilization of the laser temperature to within a few tenths of a degree. The addressing laser has a wavelength of 1532 nm and ±10 nm bandwidth, while the imaging laser has a very narrow bandwidth (±3 nm) around a center wavelength of 850 nm. Each laser is coupled through an SMA connection to a large core (400 μm diameter) fiber. The other end of the fiber is positioned within the entrance aperture of the DMD projection system.

IV. SYSTEM OPERATION

A. Image Generation in the Crystal

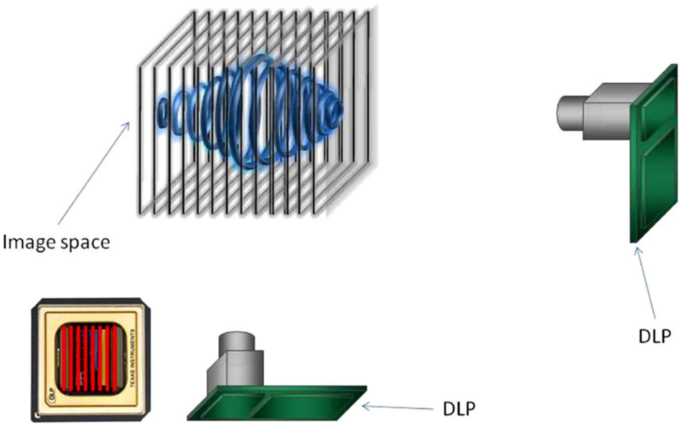

Fig. 4. Basic scheme for image generation in the optical crystal.

The primary advance in the development of our display is the method used to generate the image within the optical crystal. Fig. 4 depicts the method used for the display. The power from the addressing laser, currently at 1532-nm wavelength, is incident over the plane of a DMD. A column of mirrors is selected to direct a narrow line of light towards the crystal. This line slices through a plane of the crystal. Absorption of the laser by the crystal primes the selected plane for image creation. The imaging laser, nominally at 850-nm wavelength, is directed into the desired image pattern by a separate DMD. In comparison to the systems described previously, all of the pixels in the plane are addressed *simultaneously*, as opposed to a raster scan, which significantly reduces the addressing time and thus increases the scanning speed of the display. Each plane of the image requires one pulse from the addressing laser and one pulse from the imaging laser, as opposed to the many hundreds to thousands of pulses that may occur in a raster scan. Absorption of this second laser in the plane primed by the addressing laser provides enough energy to generate visible light detectable by the human visual system. An image forms by processing successive planes through the entire crystal and then repeating the process to refresh the current image or to create a new one. The resolution of the image increases with increases in the number of planes addressed in the crystal and the number of 2D pixels addressed within each plane. To produce the effect of a seamless image to the human visual system, however, the overall scan of the crystal must be completed in a time less than the processing time of the retina. This dictates that the entire scan of the crystal must be completed in less than 60 ms, at minimum, and ideally close to 30 ms (i.e., roughly 30 3D images per second).

A proper design of the imaging system requires control of several key parameters, including the DMD resolution and the DMD switching speed. To create a high-resolution image in depth (the horizontal direction in Fig. 4), the crystal must be “sliced” into as many planes as possible. This requires a DMD that is capable of producing a large number of patterns per second, typically on the order of 10 000 patterns per second. Note that *both* DMDs must operate at this rate, not just the DMD producing the slices, as the imaging DMD must present a new image to each slice. To create a high-resolution image across the area of each slice, the DMD associated with the imaging laser must have a large array of mirrors, as each mirror effectively represents one pixel of the image slice. In practice, the maximum speed of the mirror array, in patterns per second,

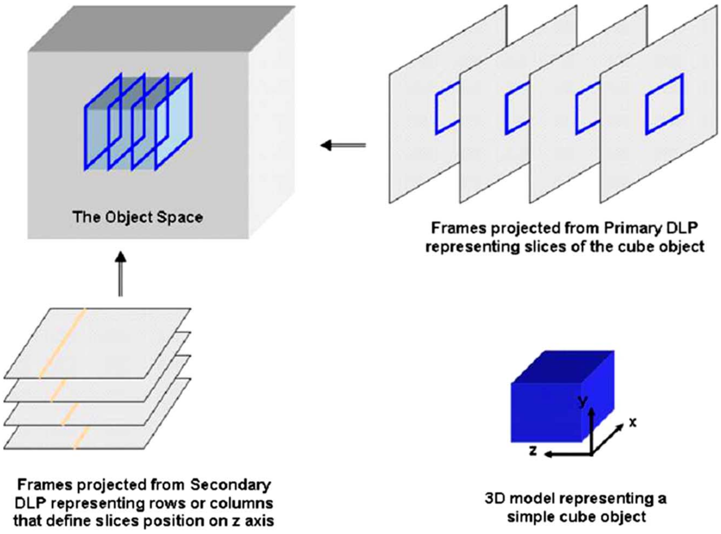

Fig. 5. Projecting 2D slices of 3D model to illuminate the model in the object space.

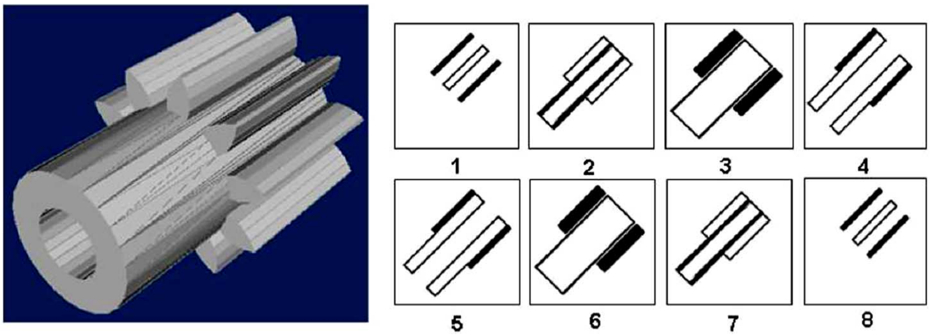

Fig. 6. An example of mechanical part 3D model with 8 2D slices cut off on the depth z-axis.

decreases as the number of mirrors in the array increases. Therefore, a trade-off exists between the speed and size of the array in obtaining an acceptable degree of overall resolution. It is important to note that the design choices for the DMD size and speed assume that a digital light projection (DLP) system exists that permit the maximum utilization of the DMD.

Also important to the design are the laser power and the range of viewing angle available to the observer of the display. The arrangement of sources depicted in Fig. 4 would limit viewing angles in the plane of the crystal, with most unobstructed views located above the crystal plane. An alternate arrangement of the imaging system will be considered in the future to improve the range of viewing angles in the display. The software driving the DLP system requires subsequent modification to properly display the image in the tilted display medium. The imaging systems must waste very little optical power to reflections or diffractions in order to promote high power efficiency for the overall system. This is particularly important when considering that a DMD can be quite lossy, and that only a slice of the addressing laser's power is in use at any one instant. Proper tailoring of the optical systems prevents most diffraction from lens and mirror edges, which also reduces the loss of power incurred when part of the optical beam is blocked by an aperture or misses an element altogether. The other main source of loss is reflections occurring at each glass-air surface of the imaging lenses. An excellent solution for reducing reflections of this type is to have anti-reflection coatings tuned to the infrared placed on the surfaces.

B. Image Rendering in Software

The CSPACE software is designed to deconstruct a 3D image imported from another source into the slices that form the basis of the image generation method. The model of a 3D object is illuminated in the object space by projecting 2D cutoff slices (images) at different positions on the depth axis. Fig. 5 illustrates how projections from both systems illuminate a cube in the object space. As an example of more sophisticated model, Fig. 6 shows a 3D model of a mechanical part created in computer graphics software, and eight possible 2D slices that should extracted from this model.

3D models are integrated into CSPACE by importing standard file formats created in any 3D modeler application. The imported 3D model is converted into a set of frames in the form of slice planes/cross sectional images cut off orthogonal to one dimension of the 3D model. The most common file format used in 3D applications is 3DS. CSPACE is capable of reading ".3ds" files.

The 3DS format uses surface rendering. Data is represented as a set of meshes or triangle strips. In VTK this kind of data is called polygonal data. Polygonal data is a collection of points

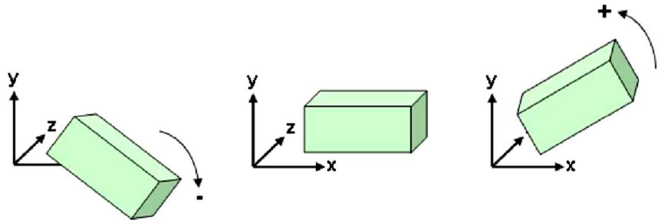

Fig. 7. Rotating 3D object around the z-axis.

and cells describing vertices, lines, polygons and triangle strips included in the model. Rendering polygonal data on the computer screen is quite fast. All 3D models are represented as a series of triangle strips in the 3DS format. The 3DS importer is capable of reading each of the 3D meshes as a separate entity. Meshes or polygonal data are then applied to the append filter to combine them all together in one poly data object.

A slicing function/algorithm is required to generate a list of slices/frames of the imported model. To extract $P(x,y)$ value for each pixel in a frame, data should be represented as volumetric containing x, y, z coordinates for each voxel in the model space. A common data representation in VTK is vtkImageData where each voxel $v(x,y,z)$ in the space is mapped to a single value called a scalar value. The vtkImageData object is a collection of points arranged on a regular lattice; rows, columns and planes. converting polygonal data extracted from the 3DS file into image data was successfully achieved using VTK.

CSPACE has several user input parameters that allow the user to control the slicing function. First, the user can select the number of slices that the object will be broken down into. The required numbers of slices will determine the spacing left between slices. Second, the user can select a rotation angle prior to slicing to fit the needs of the user or application. As shown in Fig. 7. Third, the user can control the image resolution through the slice, called the slice resolution, which corresponds to the number of mirrors in the DMD. As a default, if a resolution that is less than the DMD size in use, the extracted images are then applied to a magnification filter to fit to the screen size. Magnification could be disabled by the user and in this case the user can specify the top left coordinates (position on each frame) of the extracted image.

To minimize the distortion of the imported model while extracting slices, the slicing function should preserve the imported model height/width rate. We define Width $\boldsymbol{W}_m$, Height $\boldsymbol{H}_m$, and depth $\boldsymbol{D}_m$ as the model boundaries in each dimension. Frames will be generated by cutting on the z axis which represents the depth of the model. The frame height/width ratio in CSPACE does not necessarily match the imported model H_m/W_m ratio. This may lead to some distortion or loss of the object/model space. One possible solution to this problem is to generate slices with smaller dimensions $\boldsymbol{W}_s, \boldsymbol{H}_s$ that correspond to the model H_m/W_m ratio, and then expand the slice with empty pixels.

V. EXPERIMENTAL RESULTS

A prototype of the display system has been constructed to validate the imaging method and evaluate the system's performance. This prototype is shown in Fig. 2. The initial tests were run for a small image size of 30 slices through the crystal and a full 1024×768 resolution per slice. Only 30 slices were used for initial testing. As a result, the image was refreshed at 500 frames/s, which was significantly larger than the desired 60 frames/s, and thus producing a very steady image without flicker. The projection lens available for the output of the DMD system was coated for visible light only, and thus was removed to allow the necessary laser power to reach the crystal. A single infrared-coated lens was used as a temporary replacement and thus limited the depth of field range available to the imaging laser system.

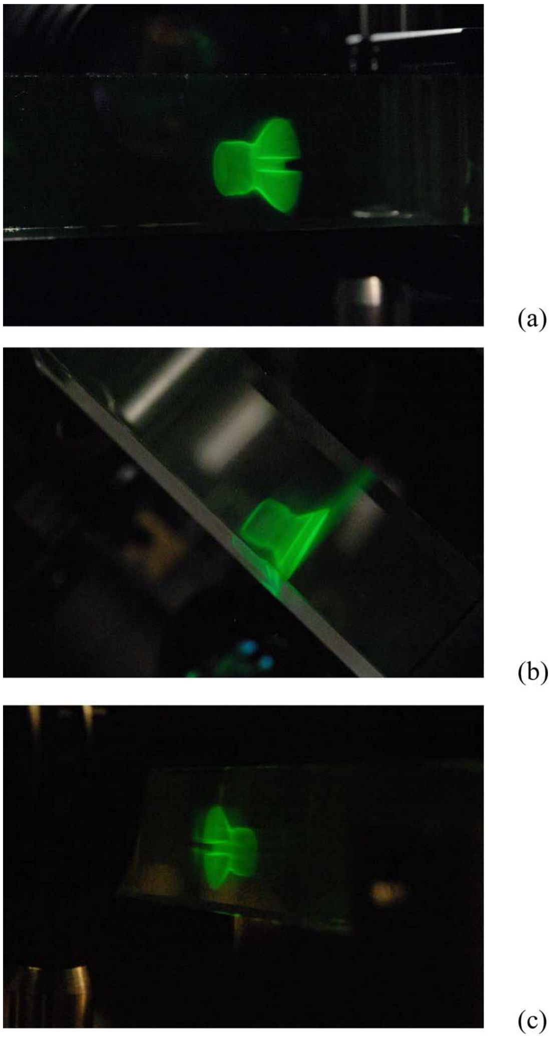
(a)
(b)
(c)

Fig. 8. Example of images produced by the display system. (a) Front view, with the screw tilted. Resolution is 90 slices with 768×1024 per slice. (b) Top view. Distortion exists due to the asymmetric divergence of the lens which is used. (c) Back view of the image where the DLP projector installed.

Given these limitations, the system still produced very good images, an example of which is shown in Fig. 8. The image resolution was 30×1024×768, resulting in almost 23 million voxels. The image is bright and easily visible from all viewpoints except those blocked by the projection systems. As noted previously, the positioning of the projection systems can be adjusted to avoid obstructing the view of an observer. The image shows good cohesion in depth and thus the slicing is not evident in the final image. This validates the design and operation of the image conversion software. The image appears sharp to the eye, though rigorous measurements of this characteristic have not yet been made. This sharpness is evidence that an effective combination of DMD resolution and proper choice of the projection lens characteristics can retain fine detail in the projected image.

While the initial experiments have been successful in producing an image, there are still many ways to improve the performance of the display. Both the imaging and addressing lasers were operated at their maximum power of 30 W due to losses in the projection modules that were higher than expected. Most of these losses were related to coupling between the input fiber and the DMD and the reflection and diffraction losses within the internal optics of the adapted units. Besides the obvious issues with the power consumption of the display, the high optical powers are also undesirable because of the potential for two-photon absorption and subsequent recombination that can produce spurious light in the image. Optimization of the optical systems to reduce the power requirements is a work in progress. The goal is to increase the throughput as much as possible to reduce the power demand of the overall display. Another avenue to explore for increasing the efficiency of the system is to increase the efficiency in converting laser power into excited electrons within the crystal. One possibility, for example, is to change the composition of the host material to increase the absorption coefficient at 1532 nm. Such a material is currently under investigation that could potentially double the absorption coefficient. We expect to produce a pixel of the same current intensity when the exposure time (pulse width) of the addressing laser is reduced by a factor of two. For a fixed area, this would result in using half of the current energy. A suitable projection lens to allow better depth control must be designed or obtained, and an updating of the DMD control boards is needed to allow more slices and thus produce larger images. With current state of the art controller boards and DMDs, we expect to be able to produce images with 1000 slices at 1024×768 pixels per slice, thus producing 800 million voxels per image. The system can be updated to three-color imagery using multiple imaging lasers, each with its own DMD, and appropriate changes in the construction of the crystal. These and other improvement efforts are currently under way.

VI. SUMMARY

In this paper, we have presented a novel volumetric display based on the two-frequency, two-step upconversion technique and DMD-based projection systems for producing the image components in a crystal. Custom-designed software converted 2D images into 3D information suitable for use with the display. The images produced by the display were sharp, bright, and free of distortion from both the slicing process and bleeding of light outside of an intended pixel into one that should not be lit. Many improvements can be made in the display system for the display to reach its full capabilities while using less optical power.

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