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Fast and continuous recording of refreshable holographic stereograms

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Abstract. We present a technique to record refreshable holographic stereograms continuously. We eliminated the translation stage that shifts the recording beams back and forth and replaced it with an uninterrupted transparent belt holding holographic lenses. The belt is driven along a perimeter, shifting the lens laterally in front of a photorefractive screen without reversing direction. The holographic lenses focus the object beam onto holographic pixels and are permanently recorded in a thin photopolymer. The photopolymer material is flexible enough for the lenses to follow the curvature of the belt when it goes around the tensioning rollers. The hogel data are uploaded sequentially onto a spatial light modulator to form the object beam. The rotation of the belt in one single direction allows for a continuous operation and a much faster recording speed than with a translation stage that needs to reverse direction at the end of its travel span. [DOI: 10.1117/1.OE.57.6.061608]

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1 Introduction

Holographic stereograms (HSs) are among the most impressive three-dimensional (3-D) images in terms of parallax and depth rendering.[1,2] They have the ability to display saturated colors, reproduce occlusion, and approximate the wavefront so some level of accommodation is provided.[3] No special glasses are required to view HSs, and there exist stunning examples of this technique being used advantageously for medical, architectural, and military applications.[4]

HSs are a class of integral imaging where the angular information is stored as holographic pixels (or hogels). Contrary to regular pixels that emit the same color and intensity in every direction, hogels diffract the light in a structured cone where the intensity and/or color can change depending on the viewing angle. This angular disparity provides different images to each of the viewer's eyes such that the brain can reconstruct the 3-D scene. Due to the large angular density that holographic recording supports, an HS provides a smooth transition among different points of view, which is not necessarily the case for other integral imaging techniques.[5]

In 2008, our group introduced the use of a photorefractive polymer screen to make the HS updatable instead of permanent.[6] Photorefractive polymers are holographic recording materials where the hologram can be erased and refreshed at will.[7] The technique was subsequently improved to increase the refreshing speed from minutes to seconds, to display full color, and to capture live 3-D images such as required for telepresence.[8]

The use of HSs for refreshable 3-D displays has several advantages over "regular" holography, as well as computer-generated holograms (CGHs). Here, we define regular holography as the interference of a reference beam with a beam reflected from the object to be recorded. This interference can be produced in either the Denisyuk[9] (reflection) or Leith and Upatnieks[10] (transmission) configurations. To be able to record the wavefront of interest, a regular holographic setup requires the "actual object" to be present on the optical table. This is not much of an issue for the production of permanent holograms, whose purpose is to be displayed at a later time and in another location. However, in the case of a refreshable hologram, whose purpose is to be erased and replaced shortly after recording, one can question the usefulness of the holographic image when the genuine object is directly accessible to the viewer.

This observation is true for a physical object, but it is also valid when the object beam is formed with the reflection from a spatial light modulator (SLM). In both cases, the holographic material only acts as a relay to record the interference pattern, and the viewer can as easily look directly at the object or SLM that is on the table. In these specific cases, the viewer would see the exact same image (or better) as the one produced by the hologram.

An updatable holographic display is only relevant if the information comprising the image can be sent over long distance, which is not the case for a regular holographic recording system.

CGH has been proposed as the mechanism to design the ultimate 3-D display. So far, this is the only technique that has been proven capable of reproducing all the visual cues.[5,11] However, this capacity comes at a very high computational cost and requires a modulator with a very high space-bandwidth product.[12,13] These demands are so stringent that, even today, there is no system capable of handling the feed for a large, high-resolution, video rate CGH display. Existing solutions, although having impressive

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accomplishments, either scale down size or resolution or rely on subaperture holograms and eye tracking.[12–14]

HSs require very little computation (unlike CGHs) and can render 3-D images from any sources (unlike regular holography). This means that either real or computer-generated models can be processed and displayed in real time. Even data cubes coming from instruments, such as radar or medical instruments, can be used to generate an HS.[15]

In our quest to improve the speed of HS displays, several fundamental factors should be considered: the recording material dynamic, the laser source repetition rate, the SLM refresh rate, and the optical setup overall speed. In regard to the hologram refresh rate, it is worth noting that since HSs are composed of multiple hogels, the writing rate of these hogels must be much faster than the overall image refreshing pace. Without taking any spatial multiplexing into account, the hogel writing rate should be equal to the image refresh rate multiplied by the number of hogels, which can easily ramp up to several kHz.

Photorefractive materials have already been shown to be capable of submillisecond response time.[16,17] Likewise, a high repetition rate (kHz) laser working with that type of material has also been presented.[18] Considering the SLM that is forming the object beam, liquid crystal on silicon technology with a maximum repetition rate of hundreds of Hz is not fast enough to support the required hogel writing rate. An alternative technology is a digital micromirror device, such as the Texas Instruments DLP®, which is capable of a binary image refresh rate of up to 32 kHz.[19]

In our past embodiments of the HS display setup, the speed of the recording was limited by the mechanical translation stage needed to scan the surface of the screen. In this article, we present a solution that avoids the use of a translation stage, allowing for a faster recording speed and supporting a fast and continuous update of the HS 3-D images.

2 Optical System Configuration

The configuration for recording of a single HS hogel is presented in Fig. 1(a). The hogel is recorded from the interference between two mutually coherent beams: a reference and an object beam carrying the information. After being spatially structured by an SLM, the object beam is focused by a lens to form a cone of light whose intensity is angularly modulated by the information displayed on the SLM. In the case of a horizontal parallax only HS [Fig. 1(b)], the beam is focused along a line using a cylindrical lens instead of a spherical lens. The entire HS is recorded when the hogels have filled the whole surface of the screen.

When replayed, the individual hogels comprising the HS diffract the reading beam into the same structured cones of light that was the object beam initially. These cones reproduce the initial angularly modulated intensity as shown in Figs. 1(c) and 1(d).

Altogether, the angularly modulated cones of light diffracted by the hogels overlap each other to form an image with both spatial and angular structure, giving the impression of parallax. The spatial extent of the hogels defines the lateral resolution of the image, while the angular resolution is given by the SLM pixel pitch and the focusing lens numerical aperture.

The advantage of a horizontal parallax only system is that it reduces the number of hogels that need to be recorded by the square root of the number needed for full parallax (size and resolution kept constant). Horizontal parallax only 3-D images are acceptable in a large number of applications

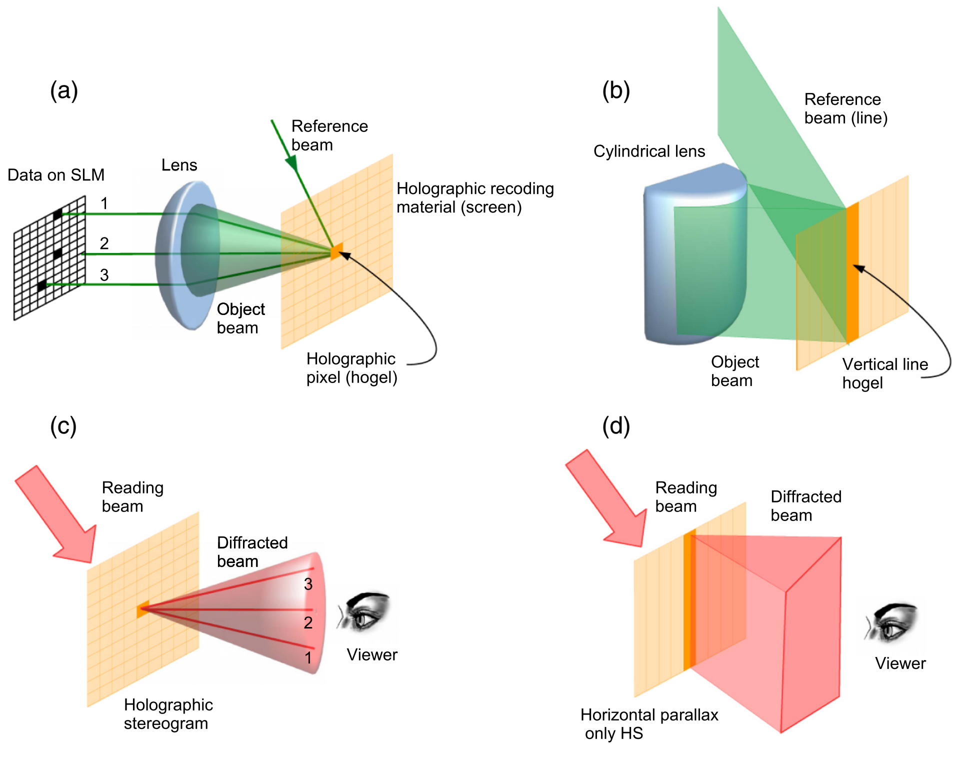

Fig. 1 Hogel recording for (a) a full parallax HS and (b) a horizontal parallax only HS. Diffraction by a single hogel during the reading of (c) an HS for full parallax and (d) horizontal parallax only HS.

because the human eye separation is along a horizontal line, and vertical parallax is only a secondary cue for depth perception.

From the hogel recording and replaying geometries presented in Fig. 1, it can be seen that the central axis of the cone forming the object beam needs to be kept parallel for every hogel. This prevents the use of a rotating mirror to raster scan the surface of the screen, and the object beam needs to be "translated and not rotated" with respect to the screen. This operation is usually accomplished using a mechanical translation stage supporting either the screen[6] or the lens and the SLM.[8]

The problem with using a translation stage is the maximum speed at which it is able to move from one hogel location to the next and the inertia of the entire system. When a CW laser is used for the recording, the displacement needs to be stopped at each hogel location and some period of time is required for the vibrations to dissipate. This is because the interference fringes must be stable during the recording.

The use of a nanosecond pulsed laser improves the recording speed because it allows for a continuous displacement instead of the stop, pause, and record procedure.[8] However, even in this case, the recording speed is still limited by the need to reverse direction and go back the entire span of the image at the end of each line of the raster. The mechanical constraints of such a system do not support recording faster than a couple of lines per second.

The solution we are presenting in Fig. 2(a) makes use of a series of holographic cylindrical lenses affixed on a rotating belt. On the same belt, and above each lens, is a slit aperture that shapes the reference beam. Figure 2(b) shows that the object beam is formed by the reflection from the SLM and then diffracted into cones by the holographic lenses. When the belt rotates, the lenses translate and the line forming the hogel spans the width of the screen. When the belt is entirely populated with lenses, the HS can be continuously refreshed without any interruption.

Although the configuration we are developing here is for horizontal parallax only, the system can easily be generalized for full parallax 3-D images. In this case, the holographic lenses should be spherical and offset vertically from one another to form a sawtooth pattern. This will ensure that the recording covers the entire surface of the screen. This configuration can be compared with a linear Nipkow disk.

The advantage of using a rotating belt instead of a translation stage is that the recording of the HS is continuous. There is no back-and-forth movement to reset the position of the lens in between each image. This continuous movement allows for a much faster speed and for the continuous refresh of the holographic image.

To take full advantage of the image refreshing capability of this system, the holographic lenses are located right next to each other, with no gap in between. This means that the separation between two recording lines is equal to the width of the lenses. This width also defines the size of the image such that, when one object beam exits the screen, a new one immediately enters at the other end of the screen.

To ensure that the entire cone of light is structured by the information displayed on the SLM, only half the lateral extent of the SLM could be used per hogel. This can be understood when looking at the moment when the last and first hogels of the image are being recorded. This case is shown in Fig. 2(b), where it can be seen that the SLM is structuring both object beams at once. Therefore, only half the SLM width is used per beam.

Because the size of the holographic lenses is much larger than the SLM, a telescope is used in the optical setup to expand the size of the object beam after the information is encoded by the SLM.

3 Optical System Implementation

A picture of the setup that we built based on the schematic presented in Fig. 2 is presented in Fig. 3. Four rollers are used to support a transparent belt made of flexible clear polycarbonate. A brushless motor from Aerotech (BMS100) is driving one of the rollers. The holographic lenses were permanently recorded into Bayfol® HX 200 photopolymer from Covestro. It can be seen in the picture that the recording beam is incident at an angle (25 deg) to the belt. The upper part is cropped by a slit aperture to form the object beam line. The lower part (not visible because it is much dimmer) is

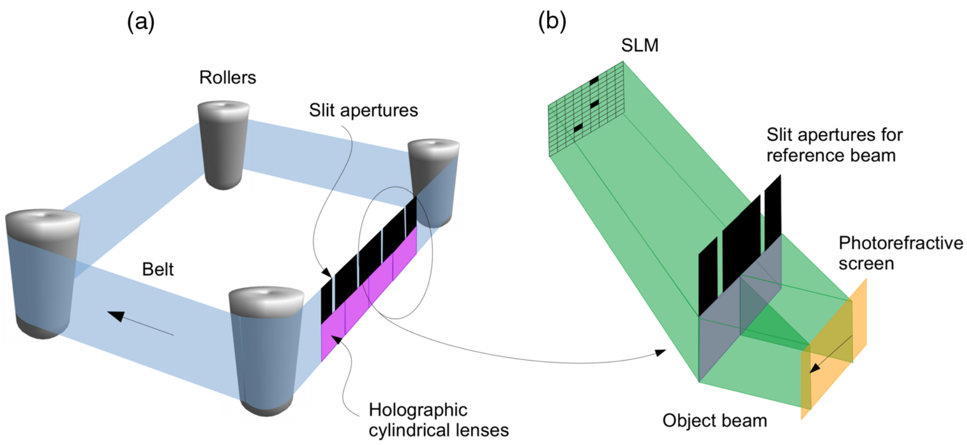

Fig. 2 Schematics of the optical setup configuration used to record the HS continuously. (a) Rotating belt driven by four rollers, the belt is holding flexible holographic lenses to form the object beam, as well as slit apertures to form the reference beam. (b) Close up of the object beam formation starting at the reflection from an SLM and focused along a line by the holographic cylindrical lenses. When the lens translates, the line scans the photorefractive screen.

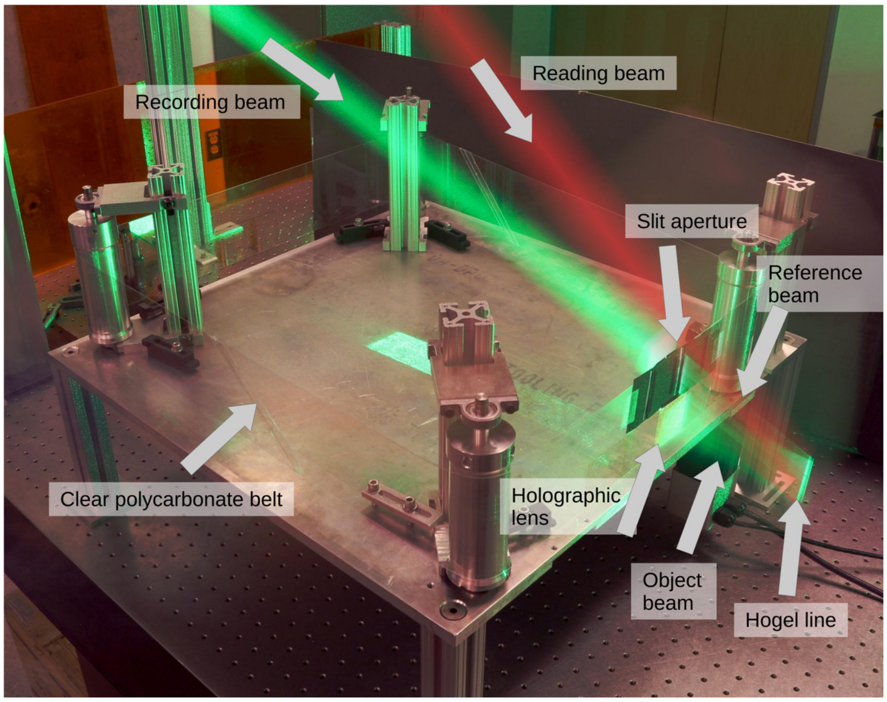

Fig. 3 Picture of the recording setup implementation based on the schematic shown in Fig. 2. Long exposure was used to capture the laser beam path. The green light is the recording beams, and the red light is the reading beam path. See text for setup details.

diffracted by the holographic lens to form a converging object beam. Both the object and reference beams superimpose into a hogel line at the location of the photorefractive screen (not present in the picture).

We designed the system so that the diffraction angle of the holographic lenses and their focal length are such that the reference beam formed by the slit aperture is coming at the same angle as the beam incident to the holographic lenses. This allows us to have only one single beam incident on the belt and reduces the number of optical elements forming the reference and object beams.

The laser source is a 6-ns pulsed doubled YAG from Innolas with a repetition rate of 100 Hz. This laser has up to 200 mJ per pulse of power with a wavelength of 532 nm. The power at the sample location was measured to be 5 mJ per pulse and per beam, which ensures good visibility of the HS image. The beam ratio was split equally (50:50) between the object and reference.

The SLM is a DLP® 7000 from Texas Instruments. It is composed of an array of 1024×768 micromirrors with a 13.68-μm pitch. The mirrors can take a ± 12- deg orientation, directing the light either to form the object beam (bright state) or to a beam block (dark state). Binary patterns can be displayed with a refreshing rate of up to 32 kHz. 8 bit gray patterns can be obtained by the vibration of the mirror and temporal integration from the human eye. However, this technique is not applicable in our case since the DLP® is illuminated with a 6-ns pulsed laser source and each hogel is recorded with only a single pulse.

The holographic screen is made of a 100-μm-thick photorefractive polymer held between two glass plates whose interior surfaces are covered with indium tin oxide electrodes. The photorefractive material is made of a copolymer with a polyacrylic backbone where tetraphenyldiaminobiphenyl (TPD) and carbaldehyde aniline (CAAN) pendent groups were attached in the ratio 10:1 (PATPD/CAAN). Fluorinated dicyanostyrene (FDCST) was used as a chromophore. To increase the sensitivity to the visible region of the spectrum, a fullerene derivative, PCBM [(6,6)-phenyl-C 61 -butyric acid methyl ester] was added. Finally, 9-ethyl carbazole (ECZ) was used as a plasticizer to lower the glass temperature. The weight ratio of the different components is PATPD/CAAN:FDCST:ECZ:PCBM (49.5:30:20:0.5 wt. %). An external electric field of 60 V/μm was applied

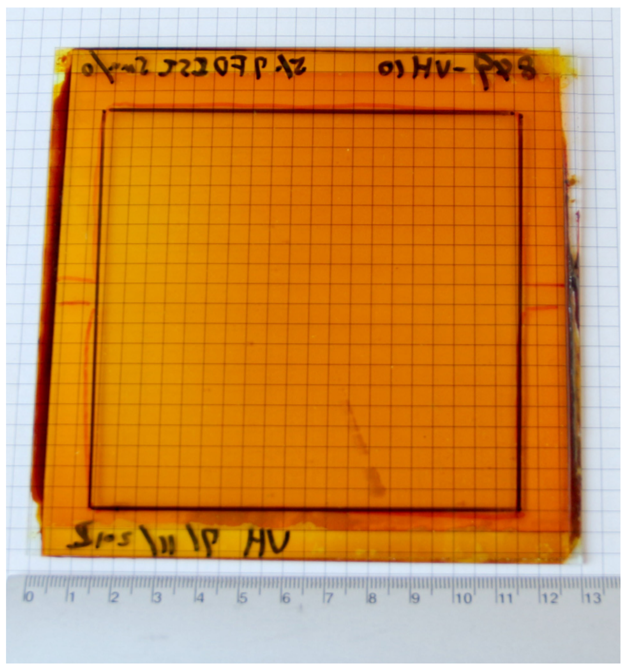

Fig. 4 Picture of the holographic screen made of photorefractive polymer. The screen active area is 10×10 cm.

to the material during the recording of the HS. A picture of the holographic screen is shown in Fig. 4.

The system is controlled by a computer using a National Instruments LabVIEW Virtual Instrumentation (VI) routine. The VI routine displays the information on the SLM, positions the belt to form the hogel at a specific location on the photorefractive screen, and triggers the laser. Since the laser pulse is only 6 ns, the belt can move continuously and does not have to be stopped during the recording. To ensure a fast refresh rate of the images, they are loaded in the computer memory before the recording procedure.

The hologram is read by a collimated red LED with a central wavelength of 640 nm and a 20-nm bandwidth. To satisfy the Bragg condition, the reading beam is incident at a larger angle than the recording beam (30 deg) (see Fig. 3), which allows it to clear the slit aperture and the holographic lens.

To protect the viewer from the pulsed laser light, an amber 2422 acrylic filter absorbing the green 532-nm light, but letting the red 640-nm reading light pass through, is placed on top of the photorefractive sample (viewer side).

4 Results and Conclusions

Some pictures of an HS recorded in our photorefractive material are presented in Fig. 5; they show that horizontal parallax and occlusion are reproduced when the viewer (or the camera) moves laterally. These two visual cues produce the impression of a 3-D image. Individual hogels, which were recorded successively, are visible as vertical lines. Some separation between the hogels was necessary to avoid overlapping and erasing of the information. It is possible to smooth the transition between hogels using a horizontal diffuser that induces apodization of the illumination function. Such a technique was not used in this case to avoid further loss in the recording beam energy.

In our particular system, the maximum refreshing rate of the HS was limited by the laser repetition rate (100 Hz). For a 100 hogels HS with a size of 40×20 mm, the recording speed is 1 s per holographic image. Although we developed a much faster laser (10 kHz),[18] it was not powerful enough (18 mJ at the source) to record the HS with enough diffraction efficiency to form a clear image. We will address this issue in future work.

The diffraction response of the material is defined by the material composition and can be found in Ref. 18. Using a 6-ns pulse, the efficiency only reaches 2% and is limited by the dynamics of the photorefractive effect, which takes a much longer time to proceed than the pulse duration. We have shown that longer pulses (>30 μs) are needed to increase the efficiency. As mentioned earlier, we developed a laser capable of such long pulses, but its limited energy did not allow for higher efficiency compared with the more powerful Q-switched doubled YAG laser that was used in this setup.

It should be noted that the recording speed is not limited by the laser energy per pulse but rather by the laser repetition rate. The energy per pulse, however, defines the diffraction efficiency and, thus, the image luminous intensity.

The cost of the entire system is mostly driven by the laser, which is a nanosecond doubled YAG with 200 mJ per pulse. Such a laser usually costs a couple of hundred thousand dollars. The next most expensive components are the linear motor driving the belt and the SLM. Both of which cost several thousand dollars. The price of the optics is negligible in comparison. It might be possible to use a cheaper laser if the power is scaled down. However, this would require a more efficient setup or a more sensitive photorefractive material.

To make a more compact system, it would be possible to replace the belt and the holographic lenses with an SLM that displays Fresnel diffraction lenses. This second SLM would diffract the laser light to form the object beam cone with shifting focal location. The focal location should be synchronous with the hogel data displayed on the first SLM. We did not implement this solution because of the reduction of energy due to the lower efficiency of the SLM compared with a holographic lens recorded on photopolymer and the limited angle that the SLM can diffract (a few degrees). However, the advantage of using an SLM instead of the rotating belt would be to make the system much more compact and avoid the potential mechanical fatigue of the belt. Future SLM technology, such as a microelectromechanics system composed of micron scale phase shifters, could made this implementation feasible.

It is also possible to record full parallax HS with a similar system. To do so, the cylindrical lenses forming the object beam need to be replaced by spherical lenses. To take care of the vertical scanning, the spherical lenses should be staked in a sawtooth configuration as shown in Fig. 6, so each lens is scanning a different row when the belt is moving. To

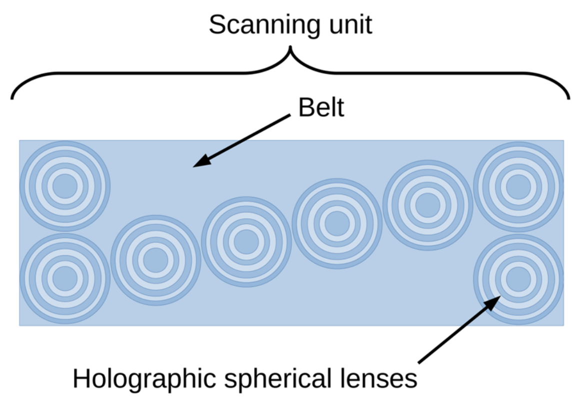

Fig. 6 Sawtooth configuration of the spherical lenses to record a full parallax HS. This configuration is repeated over the entire length of the belt.

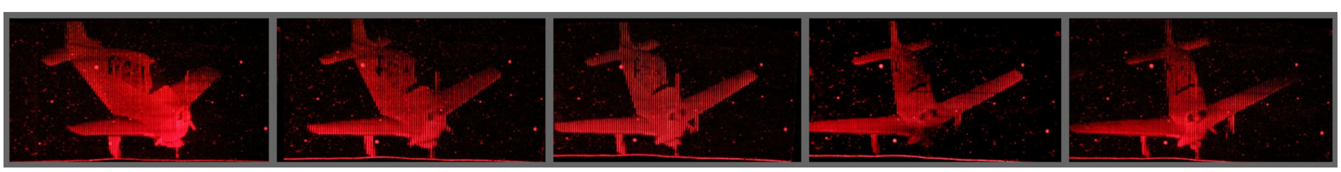

Fig. 5 Picture of an HS recorded in photorefractive material showing parallax and occlusion when the camera is moved laterally.

eliminate the apertures forming the reference beam, an unexpended beam can be steered from far away so it reduces any angular artifact.

The system we are presenting in this publication is capable of fast and continuous recording of refreshable HSs. This is a step toward the development of an autostereoscopic 3-D television with the reproduction of motion parallax and occlusion.

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Colton Bigler is a fourth-year PhD student at UA's College of Optical Sciences. During his time at UA, he has worked in the 3-D holography lab, where he designed and implemented a physical demonstrator for avionic heads-up display applications. He graduated cum laude from the Colorado School of Mines with his BSc degree in engineering physics.

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