Digital holographic three-dimensional display of 50-Mpixel holograms using a two-axis scanning mirror device

Ridwan Bin Adrian Tanjung
Xuewu Xu
Xinan Liang
Sanjeev Solanki
Yuechao Pan
Data Storage Institute
A*STAR
5 Engineering Drive 1
Singapore 117608
E-mail: XU_Xuewu@dsi.a-star.edu.sg

Farzam Farbiz
Institute for Infocomm Research
A*STAR
1 Fusionopolis Way
#21-01 Connexis
Singapore 138632

Baoxi Xu
Data Storage Institute
A*STAR
DSI Building
5 Engineering Drive 1
Singapore 117608

Tow-Chong Chong
Data Storage Institute
A*STAR
DSI Building
5 Engineering Drive 1
Singapore 117608
and
National University of Singapore
Department of Electrical and Computer Engineering
4 Engineering Drive 3
Singapore 117576

1 Introduction

Holographic display is a true 3-D display technology that has the ability to spontaneously present all depth cues from multiple views. The technology does not depend on any visual aids and promises no visual fatigue to the human visual system. As such, it is considered the ultimate 3-D display technology with market potential for various applications in the near future.1

According to Stanley et al.,2 the displayed image size of 3-D objects depends proportionally on the number of pixels of the hologram. As such, increasing the hologram pixel count for a specific field of view and wavelength enable us to increase the image size of reconstructed 3-D objects.

With this in mind, for a full parallax holographic 3D display with a 7-in. diagonal image size and a 20 deg field of view will require about $4.5 \times 10^9$ pixels. This is still a few orders of magnitude beyond the pixel count of single spatial light modulators (SLMs) currently available in the market. As an example, one of the advanced projectors by NHK and JVC contains a liquid-crystal-on-Silicon (LCOS)–based SLM that can demonstrate3 35 Mpixels (8192 × 4320 pixels), which is still about 120 times less than the requirement to produce a holographic 3-D display system with the displayed image size already mentioned.

Various implementations of holographic 3-D display technology have been achieved by different groups all over
to the world. To solve the problem of the limited pixel count of a single SLM, one approach is to replicate SLM itself by using Qinetiq’s active tiling (AT) system. The AT system utilizes a set of replication optics to produce multiple images of an electrically addressed SLM on an optically addressed SLM (OASLM). The display of a 100-Mpixel computer-generated hologram (CGH) was demonstrated with their holographic 3-D display system.

Another approach is to physically increase the number of SLMs, as proposed by a research group in Japan called Telecommunication Advancement Organization (TAO). They used five LCDs arranged horizontally, which resulted in a total pixel count of about 15 Mpixels (16,000 × 960 pixels). In these displays, a large image and a wide viewing zone were obtained, but the vertical parallax was discarded.

Research institutes such as the Massachusetts Institute of Technology (MIT) and the Institute of Symbiotic Science and Technology, Tokyo University of Agriculture and Technology, have each developed a holographic 3-D display system using the horizontal-parallax-only (HPO) approach. Their approach involves scanning a 1-D horizontally limited parallax line hologram using galvanometric scanners to form a 2-D hologram on a vertical diffuser. These displays sacrifice vertical parallax to reduce the resolution requirement for the SLM. Large-size images with wide viewing angles were also achieved using the HPO approach.

It is observed that the approaches employed by Qinetiq and TAO (Refs. 4 and 5) involve tiling of subholograms predivided from a reconfigurable CGH with a high pixel count before reconstructing the tiled CGH, whereas the HPO approach requires scanning 1-D holograms onto a vertical diffuser to form a 2-D hologram on a vertical parallax. These displays sacrifice vertical parallax to reduce the resolution requirement for the SLM. Large-size images with wide viewing angles were also achieved using the HPO approach.

In this paper, we introduce a new approach whereby subholograms computed for the subobjects that were predivided from a single 3-D object are reconstructed before tiling them in space. In our system, full-parallax binary digital subholograms instead of linear HPO holograms are first launched onto a high-speed digital micromirror device (DMD). A true holographic 3-D subobject is be reconstructed by illuminating the subhologram on the DMD with a red laser. The reconstructed subobjects are finally time-sequentially tiled using a two-axis scanning mirror device. Our presented system only uses one DMD and does not require an OASLM for hologram tiling or a vertical diffuser. We also present a new tiling sequence and a shutterless system design to enable effective tiling of subobjects reconstructed from subholograms to achieve a 50-Mpixel display.

2 System Overview

Our holographic 3-D display system consists mainly of a DMD, a two-axis scanning mirror device, a 50-mW continuous wave (cw) red laser diode at 655 nm, telecentric f-theta scanning lenses, and mirrors. The DMD device from Texas Instruments consists of a DMD chip (0.95-in. diagonal, 10.8 μm, 1920×1080) connected to a Digital Light Processing (DLP) Discovery 4000 starter kit (Digital Controller Board DCB4000). An Accessory Light modula-

Downloaded From: https://www.spiedigitallibrary.org/journals/Optical-Engineering on 30 May 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use
3 System Control and Synchronization Using LabVIEW Software

A program was developed using LabVIEW software to control and synchronize the DMD with the scanning mirror device. The interface for the program is a graphical user interface (GUI) (see Fig. 2) that enables users to simply select CGHs to be displayed. A flowchart for controlling and operating our holographic 3D display system is shown in Fig. 3.

The GUI in Fig. 2 shows the available CGH folders from a Listbox [see Fig. 2(a)]. From this listbox, users select the folders representing the 3-D objects to be displayed. The selected CGHs are then listed in another panel [see Fig. 2(b)]. This CGH selection sequence is indicated by the section of the flowchart shown in Fig. 3(a). In the meantime, the information obtained from the selected CGH folder is processed by the system control program working in the background that controls the DMD as well as the scanning mirrors. Users can control the loading of CGHs and select the display mode by clicking on the buttons, as indicated by Fig. 2(c). The interface also contains system indicators to show the current status of the devices as well as to warn users of any errors that have occurred [see Fig. 2(d)].

The DMD control program performs tasks such as initialization of the DMD and memory allocation for the CGH frames [see Fig. 3(b)]. Timing parameters and synchronization modes are controlled from the program. Synchronization modes determine whether the DMD launches CGH frames independently without synchronizing with the scanning mirror device for single object projection (master mode) or in sync with the scanning mirror device for tiling of reconstructed subobjects (slave mode). The program also contains subprograms to communicate with the scanning mirror device and load the necessary scan jobs. The scan job is a job file containing the scanning sequence of the mirrors as well as other timing parameters [see Fig. 3(c)].
4 Noninterruptible Tiling Sequence of Reconstructed Subobjects

In our system, we were able to display fully tiled 3-D objects without apparent flickering effect at a refresh rate of 25 fps. This refresh rate corresponds to a period of 40 ms for a whole tiled frame. Conventional tiling sequences that could be used to tile the reconstructed subobjects are raster and boustrophedral tiling sequences. As an example, 48 subholograms computed for 48 subobjects predefined from a single 3-D object are tiled following the sequence indicated by the number within the tiles shown in Fig. 4. The dotted lines show the large jump steps taken by the respective tiling method. Figures 4(a) and 4(b) illustrate the raster and boustrophedral tiling sequences, respectively.

Both the raster and boustrophedral tiling sequences are not continuous due to the large jumps caused by retrace and/or flyback steps. For the raster tiling sequence, this discontinuity is evident in the retrace step when tiling of subobjects reaches the end of every row or during the flyback step on reaching the end of the frame. The discontinuity in the boustrophedical tiling sequence is present during the flyback step when tiling of subobjects has reached the end of the frame. Since the large jumps require a longer time to move and stabilize the scanning mirrors as compared to the continuous movement between adjacent tiles, the preceding two tiling sequences are not efficient.

In our system, we have adopted a new noninterruptible tiling sequence without any retrace and/or flyback steps. As shown in Fig. 4(c), no large jumps are necessary throughout the tiling process of a whole frame. During the tiling process, both $X$ and $Y$ axis scanning mirrors move in a “stop-and-go” manner, i.e., after the scanning mirrors project each reconstructed subobject onto its corresponding tile position in space, the mirrors are then moved to the next position and are stabilized before projecting subsequent reconstructed subobjects. This whole process is controlled by the LEC—1 controller card. To implement the noninterruptible tiling sequence of 48 subobject tiles (6 rows $\times$ 8 columns), as shown in Fig. 4(c), the card outputs $X$ and $Y$ axis voltage signals to the servo drivers. These drivers are responsible for actuating the $X$ and $Y$ axis scanning mirrors according to the timing diagram shown in Fig. 5. The flat regions of the $X$ and $Y$ axis voltage signals correspond to the stabilization of the $X$ and $Y$ axis scanning mirrors to project a reconstructed subobject from the DMD to a specific column and row position in space. The DMD projects only a single subhologram when the controller card issues a 5-V logic high-synchronization signal to the DMD device.

The settling time of the mirrors is dependent on the mirror jump speed and the distance between two tile positions. When an input step voltage is being sent to the servo drivers, it will result in the actuation of the mirrors. The higher the input voltage, the larger will be the scanning mirror deflection. The input voltage to the servo driver was varied for the full range of the servo driver ($\pm$ 10 V) and the corresponding scanning mirror position response was studied to establish the relationship between the change in input step voltage and settling time, as shown in Fig. 6(a). The settling time of the scanning mirror was obtained with an oscilloscope by measuring the time taken for the scanning mirror position to actuate from initial position upon application of the input step voltage to 99% of the final stabilized position of the scanning mirror. The position of the scanning mirror is indicated by the voltage signals tapped from position detectors within the servo drivers, which are read from the oscilloscope. The experimental results from Fig. 6(a) show that as the change of input voltage ($AV$) increases, the settling time also increases. This poses a limitation on how fast the tiling can be done as the scanning mirror does not jump to a certain tile location instantaneously.

Large input voltages are required to achieve the large jumps from row to row (raster tiling sequence) and to perform the large jump from end of the frame back to the first tile location (raster and boustrophedral tiling sequences). These large input voltage values cause a longer settling time for the mirrors and the accumulation of these large jumps inevitably causes the tiling to be slow.

By considering the settling time from tile to tile, a comparison of the total time taken to tile all the subobjects with different tile numbers, as listed in Table 1, using raster, boustrophedral, and the noninterruptible tiling sequence is shown in Fig. 6(b). We assume that a tile size of 0.25 $\times$ 0.3 in. is used, and the distance between the mirrors and the tiling screen is 25 cm. According to the scanning mirror device specifications, 1 V of input voltage corresponds to 2 deg of angular mirror deflection. This relationship was used to calculate the settling time. Table 2 further compares the difference in total time between the noninterruptible...
and raster as well as boustrophedral tiling sequences. We can see from Fig. 6/H20849b/H20850 and Table 2 that the noninterruptible tiling sequence shows an advantage over the raster or boustrophedral tiling sequence.

5 Implementation of Shutterless System Design Using the Black Frame Method

During the transition from one DMD frame to the next, a “sweeping effect” is observed if the laser is not blocked, as shown in Fig. 7(a). Conventionally, high-speed shutters are used to block the laser when the scanning mirror actuates from one tile location to another.

Mechanical shutters have some disadvantages as they have a limited switching bandwidth. Actuating the mechanical shutters too fast will result in mechanical failure. Slowing down the mechanical shutter to prevent mechanical failure will adversely affect the tiling rate. On the other hand, optical shutters are two state devices that can transmit and block a light path in the on and off state at high speed using liquid crystal devices. These components can reach a switching speed higher than 50 kHz. However, the disadvantages of using optical shutters are that it could not reach 100% transmission in the on state. Using optical or mechanical shutters requires additional space in the display system as well as extra driver circuitry and programming to synchronize the device with the DMD frames.

Modulatable lasers are a better alternative compared to the optical and mechanical shutters. This is because the laser transmission is controlled by the laser itself instead of using additional hardware. As a result, the system footprint remains the same. However, similar to the optical and mechanical shutters, this will incur extra circuitry to drive the modulatable laser to synchronize with the DMD frames.

The method implemented in our system takes advantage of the DMD itself to transmit and block light to the scanning mirrors. During the transition from one frame to the other, a black frame is launched onto the DMD. This prevents the laser illuminating the DMD surface from being reflected to the scanning mirrors. During the time period when the black frame is launched, the scanning mirrors will move from one tile to the next tile location, which will not cause the sweeping effect. As the DMD has a high frame rate of up to 6 kHz, high-speed tilting is achievable without the use of any extra shutters or modulated lasers that require extra circuitry for control signal synchronization.

Subobjects reconstructed from the DMD that will eventually be tiled using the scanning mirror device to form the whole 3-D object had to be time sequentially launched and synchronized with the scanning mirrors. The timing diagram to synchronize the scanning mirror device with DMD and black frame insertion is shown in Fig. 8. The BF is launched only when the mirror is moving from one location to the next. When the mirror stabilizes, the controller card sends a signal to the DMD to launch the subhologram. Throughout the process, the laser source is constantly on. Figure 7(b) shows the result after implementing the BF insertion method between two reconstructed subobjects 1 and 2.

To test this idea further, the BF insertion method was implemented to tile 120 subholograms (12 rows × 10 col-
6 Tiling of 24 Reconstructed Subobjects Using a Scanning Mirror Device

As a proof of concept to display a tiled 3-D object from reconstructed subobjects with high pixel counts using a two-axis scanning mirror device, we successfully displayed a holographic 3-D teapot from our display system [see Fig. 10(a)]. The 3-D teapot in Fig. 10(a) was obtained by tiling 24 reconstructed subobjects using the noninterruptible tiling sequence. These subholograms were computed from subobjects obtained by predividing a computer-generated model of a 3-D teapot, as shown in Fig. 10(b). We also implemented the BF insertion method between subobjects to remove the sweeping effect.

With each subhologram having a pixel count of 1920 × 1080 pixels, the teapot in Fig. 10(a) has a total pixel

Table 1 Diagonal dimension of tiled screen with different tile numbers.

<table>
<thead>
<tr>
<th>No. of Tiles</th>
<th>No. of Rows</th>
<th>No. of Columns</th>
<th>Diagonal Dimension (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>6</td>
<td>4</td>
<td>1.9</td>
</tr>
<tr>
<td>48</td>
<td>8</td>
<td>6</td>
<td>2.7</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>120</td>
<td>12</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>168</td>
<td>14</td>
<td>12</td>
<td>5.0</td>
</tr>
</tbody>
</table>
count of about 50 Mpxels. As compared to a reconstructed 3-D teapot obtained from a single DMD frame, the image size has increased proportionally with the number of sub-objects tiled. Currently, our display system has a maximum image size of approximately $70 \times 30$ mm with a small viewing angle of about 5 deg. We are still investigating to further improve our system performance in terms of these two parameters.

Note also that the maximum number of subobjects that could be tiled is not limited to 24, as Fig. 9 proves that the system could tile 120 subobjects, which could produce a display of 240 Mpxels. As the scanning mirrors have a minimum response and stabilization time, the maximum number of subholograms that could be tiled within a certain time, e.g., 40 ms, is limited. Limitations from the scanning mirrors and the DMD also limit the maximum achievable refresh rate of the fully tiled reconstructed subobjects. The 25 fps refresh rate of our current system can be further increased by using a higher tiling frequency of scanners and higher DMD refresh rates.

Another issue related to our approach is the quality of the tiled 3-D object. The quality is highly dependent on the

<table>
<thead>
<tr>
<th>No. of Tiles</th>
<th>$t_1$ (ms) for Noninterruptible</th>
<th>$t_2$ (ms) for Boustrophedral</th>
<th>$t_3$ (ms) for Raster</th>
<th>$\Delta t_1 = t_2 - t_1$ (ms)</th>
<th>$\Delta t_2 = t_3 - t_1$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>9.5</td>
<td>11.0</td>
<td>19.0</td>
<td>1.5</td>
<td>9.5</td>
</tr>
<tr>
<td>80</td>
<td>16.2</td>
<td>17.9</td>
<td>30.1</td>
<td>1.7</td>
<td>13.9</td>
</tr>
<tr>
<td>120</td>
<td>24.6</td>
<td>26.4</td>
<td>43.4</td>
<td>1.9</td>
<td>18.8</td>
</tr>
<tr>
<td>168</td>
<td>34.7</td>
<td>36.9</td>
<td>59.1</td>
<td>2.2</td>
<td>24.4</td>
</tr>
</tbody>
</table>

| Table 2 | Comparison of total time differences between the noninterruptible and raster as well as boustrophedal tiling sequences. |

Fig. 7 (a) Sweeping effect observed between two reconstructed sub-objects and (b) removal of sweeping effect with the black frame insertion method.

Fig. 8 Timing diagram for insertion of black frames (BFs) between subobjects SH$n$, where $n$ refers to subobject sequence.
alignment and attributes of each reconstructed subobject. As a well-defined alignment of the subobjects is difficult, overlapping of the tiles occurs. This overlapping degrades the uniformity of the tiled 3-D object, as can be seen by certain parts of the 3-D teapot spotting higher intensity due to the summation of intensity at the overlapping region. Furthermore, optical distortion (barrel distortion, as can be seen from Fig. 9) in the tiled reconstructed subobjects due to the use of telecentric lens also affected the quality of the 3-D object. We are currently investigating these issues to overcome the problems encountered and results will be reported in the future.

Nevertheless, this system has been able to produce a higher pixel count compared to a single DMD frame. By using a more advanced scanning mirror device together with the approach demonstrated in this paper, the number of subholograms that could be tiled can be increased and scaled to realize a gigapixel-level display in the future.

7 Conclusion

We developed a new approach to achieve a 50-Mpixel display with a maximum image size of 70 × 30 mm of a full parallax 3-D object by tiling 24 reconstructed subobjects computed from a predivided 3-D object. A 240-Mpixel-scale display is achievable with our current system as it has the potential to tile up to 120 subobjects. The tiling is done by using a two-axis scanning mirror device with a noninterruptible tiling sequence. A BF insertion method is adopted to remove image sweeping effect, which enables the implementation of a shutterless system design for effective tiling of subobjects. Despite modest results, our approach provides a scalable solution for future gigapixel-level displays.

Acknowledgments

This work is funded by HOME2015 Programme of A*STAR, Singapore. We would like to thank our students, Mr. Rajee Mohamed and Mr. Zhang Jingxiang from Nanyang Technological University for their contributions to the graphical user interface design and programming for our holographic 3-D display system.

References


7. Conclusion

We developed a new approach to achieve a 50-Mpixel display with a maximum image size of 70 × 30 mm of a full parallax 3-D object by tiling 24 reconstructed subobjects computed from a predivided 3-D object. A 240-Mpixel-scale display is achievable with our current system as it has the potential to tile up to 120 subobjects. The tiling is done by using a two-axis scanning mirror device with a noninterruptible tiling sequence. A BF insertion method is adopted to remove image sweeping effect, which enables the implementation of a shutterless system design for effective tiling of subobjects. Despite modest results, our approach provides a scalable solution for future gigapixel-level displays.

Acknowledgments

This work is funded by HOME2015 Programme of A*STAR, Singapore. We would like to thank our students, Mr. Rajee Mohamed and Mr. Zhang Jingxiang from Nanyang Technological University for their contributions to the graphical user interface design and programming for our holographic 3-D display system.

References


Xuewu Xu obtained his BSc degree from Nanjing University and his PhD degree from the Chinese Academy of Sciences (CAS). He is a research scientist with the Data Storage Institute. His research interests include holography for 3-D display and high-density data storage, holographic media, and crystal materials. He is a member of the Society for Information Display (SID) and a member of International Organizing Committee of International Workshop on Holographic Memories & Display (IWHM&D).

Xinan Liang is a senior research fellow in optical materials and system division at Data Storage Institute (DSI), A*STAR, Singapore. He received his BSc degree in 1992 from Lanzhou University, his MSc degree in 1997 from the Chinese Academy of Space Technology (CAST), and his PhD degree in 2000 from the Chinese Academy of Science (CAS). His current research relates to holographic data storage media and holographic display technology.

Sanjeev Solanki received his MS degree from the Indian Institute of Technology, New Delhi, and his PhD degree in electrical and computer engineering from the National University of Singapore. His research focus includes optical and electroholography for application to high-density optical data storage and holographic TV.

Yuechao Pan received his BEng degree in computer engineering from National University of Singapore in 2008. He is currently a research engineer with Data Storage Institute, A*STAR, Singapore. His main research interest is fast computer-generated hologram (CGH) computation and hardware integration for holographic 3-D display systems. He is a member of IEEE and ACM.

Farzam Farbiz received his PhD degree in 1999 from the Amirkabir University of Technology, Tehran, Iran. His PhD thesis was on computational intelligence filters for image enhancement. He received the first rank of the national young researcher award in 1999 as the best Iranian young researcher. Since 2006 he has been a senior research fellow and principle investigator on a multimodal game engine and mixed reality system for home application projects with the A*STAR Institute for Infocomm Research. He is also collaborating with A*STAR Data Storage Institute on developing laser holographic display systems. He has published more than 60 papers in international conference proceedings and journals and has served as technical reviewer and program committee member for many international journals and conferences.

Baoxi Xu is a senior scientist with the Data Storage Institute. He received his PhD degree from Tsinghua University in electro-optics in 1994. He has been with the Data Storage Institute since 1995. His research interests include optical data storage, hybrid high-density data storage, 3-D display, and surface plasmon applications.

Tow-Chong Chong obtained his BEng degree from the Tokyo Institute of Technology, his MEng degree from the National University of Singapore (NUS), and his ScD degree from the Massachusetts Institute of Technology, all in electrical engineering. He is currently the executive director of the Science & Engineering Research Council of A*STAR and executive director of the Data Storage Institute. Prof. Chong’s research interest is magnetic and optical data storage, especially in advanced thin films and devices for ultra-high-density recording. His other research interests include high-speed electronic and optical devices. Prof. Chong is also a professor with the Department of Electrical and Computer Engineering, NUS. He has authored and coauthored more than 300 publications in international refereed journals, presented 23 invited talks, and holds 20 patents. He served as cochair of APMRC2008 and as a member of the Technical Program Committee for ODS (United States), ISOM (Japan), APDSC, MORIS (Japan), CLEO Pacific (United States), and OECC (Japan).