様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Light field 3D display using non-planar holographic lens array screen

研究課題名（英文）Light field 3D display using non-planar holographic lens array screen

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　13,400,000円

研究成果の概要（和文）：湾曲した3Dディスプレイを開発し、その試験運転を行った。このディスプレイを用いて視野角10度の20cm×10cm×5cm（奥行）のアニメーション3D像を裸眼で観察できた。この表示システムは、市販のプロジェクターとホログラフィックマイクロレンズアレイシート（自作）のみで構成されている。主な成果は、１）誰でも可能な全自動キャリブレーション法の開発、２）ホログラフィックレンズアレイシートを自作の印刷システムで曲面スクリーンとして印刷、３）3D像から2Dプロジェクタに表示するデータを計算する新しいアルゴリズムの開発、である。

研究成果の学術的意義や社会的意義
The developed flexible 3D display requires only a 2D projector, a special micro-lens sheet and computed 3d scene data. The user can view the 3D scene of size 20cm x 10cm x 5cm(depth) without technical skill. It can be used as 3D head-up displays in car wind shield, home windows (smart windows) etc.

研究成果の概要（英文）：Curved light field 3D displays were developed and tested. An animated 3D-scene of size 20cm x 10cm x 5cm (depth) can be successfully viewed in 3D using naked eye for a viewing angle of 10-degrees. The display system is very simple and consists of only a commercial projector and holographic micro-lens array sheet (fabricated by us). The key achievements are 1) development of a fully automatic calibration method that can be used by any one, 2) printing holographic lens array sheet as a curved screen using home-grown printing system, 3) new algorithm for computing data to be displayed on the 2D projector from a 3D-scene.

研究分野：Holography

キーワード：3D displays　Light Field displays　Holography　Hologram printing　Calibration

１．研究開始当初の背景

Light field displays are promising candidate for next generation 3D displays. Light field displays combine a 2D display with a lens array sheet to generate the 3D images. The main issues that block the commercial success of light field displays are i) the difficulty in fabricating large-size lens array sheet to ideal specifications, ii) complex nature of the 3D display system itself. We have developed new method of fabricating lens-array sheets using ‘digital hologram printing technique’, which could be fabricated to very large size (30 cm x 30 cm) with each elemental lens having a focal length of 2.15mm. This helped to overcome the issue (i). The micro-lens arrays (hologram sheet) were fabricated not only with micro-lens functions but with a variety of other optical functions as well (multifunctional lens array sheet). This complex nature of lens array significantly reduced the complexity of the display system and hence aided as a solution to issue(ii). But the hologram screen was flat which limited its viewing angle and adaptability to arbitrary usage environment (eg. on the wind shield of a car whichis curved). So, it is necessary to investigate the possibilities of realizing a curved light field display by fabricating a micro-lens array sheet in curved form. This will open several possibilities for light field displays to satisfy future 3D display requirements, especially in Augmented reality and Virtual reality arena.

２．研究の目的

To realize a curved 3D display, it is required to re-investigate and develop all the modules of the display system from scratch. This involves a) fabricating a multifunctional holographic micro-lens array sheet in curved from, b) rendering elemental images from a 3D-scene in accordance with the curved lens array screen, c) development of a calibration procedure that aligns the projector pixels with lens-array positions and d) building of the display system and testing the results. Realizing the above mentioned four-steps will be the original contribution from this research.

３．研究の方法

The above mentioned four-steps in the proposed research were completed as follows,

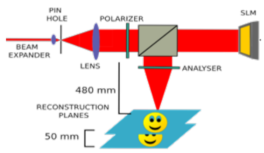

Figure 1. Schematic of Hologram Printing system

a) Fabrication of curved lens-array screen: The hologram data required to fabricate the micro-lens array screen was calculated. This calculation included the lens function + various tilt functions + curved display specifications. The complex hologram data was then used to print the micro lens array screen using a home-grown dedicated hologram printing system shown in Figure.1. The holographic micro-lens array sheets were fabricated on a flexible photopolymer sheet (purchased from Covestro co. Ltd.). Initially flat lens-array sheets of size 20 cm x 10 cm were fabricated for testing purposes. These sheets had 200x200 elemental micror-lenses, each with a size of 1mm x 0.5mm and focal length of 2.15mm. The flat lens array-sheets were then bent into a curved configuration by placing it in a curved enclosure as shown in Figure.2 Several fabrication trials had to be conducted to reach a better-quality lens array sheet.

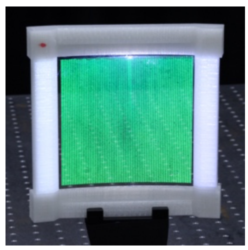
Figure 2. Photograph of Fabricated curved lens-

b) Rendering integral images from 3D-scene: The 3D-scene to be display is modelled in the computer (Figure.3a) and the 3D rendering software 'Blender' was used to render the integral (IP) images (Figure-3b). The rendering engine of Blender was customized according to the curved display requirements. This made the rendering slow which took 48-hrs to render a 90-frame animation with a frame size of 2180 x 4096 pixels. So, we developed a dedicated

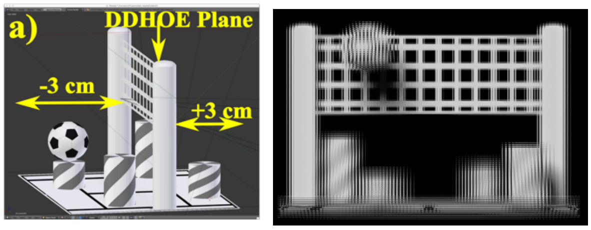

Figure 3. a) The modeled 3D-scene, b) the rendered IP image

GPU algorithm that could complete the same task in 2-hrs by utilizing parallel rendering capabilities. The computed IP images were then displayed on a 2D projector and projected on the lens-array screen.

c) Calibration of display system: Light from each projector pixel must reach the pre-destined position on each micro lenses for an accurate reconstruction of 3D-scene. This was the most difficult step among all since the projector display was flat, but the lens-array screen was curved. A camera (canon EOS Mark-II) was used for calibration as shown in Figure.4 (a). We implemented the novel idea of printing small diffuse areas on the corners of each elemental lenses which acts as markers in the calibration process (Figure-4.b). The developed method was robust and fully automatic and does not require any manual intervention during calibration. The effects of calibration are shown in Figure.5

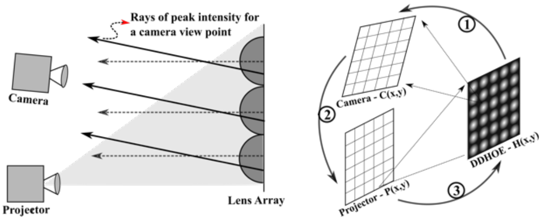

Figure 4. a) Schematic of the calibration setup, b) Diffuse areas in lens array screen serve as markers for robust calibration.

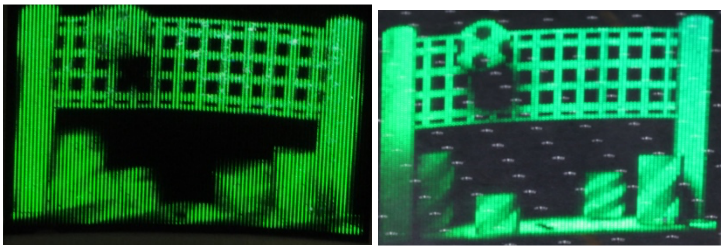
Figure 5. a) Reconstructed image before calibration, b) Reconstructed image after calibration using diffuse corners as markers.

d) Build display system: The 3D display system is simple and consisted of a commercial 2D projector with 4096 x 2180 pixels. A camera was placed in the view zone to calibrate the projector with respect to lens-array screen. Once the calibration is over, the IP images rendered from 3D scene are displayed on the 2D projector. The light rays from the 2D projector fall on the micro-lens array screen which converts the 2D information into 3D light-field images. A photograph of the display system is shown in Figure.6

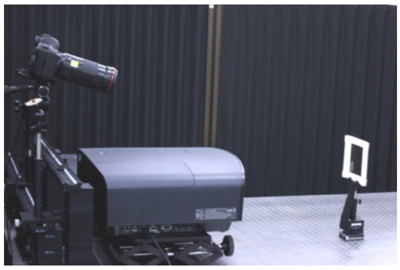
Figure 6. Photograph of the display system

４．研究成果

3D-scene of size 10cm x 10cm and 20cm x 10cm were successfully reconstructed for a viewing angle of 20-degrees and 10-degrees respectively. The scene depth was around 5 cm and further increase in scene depth caused blurring. The 3D reconstructions could be viewed freely by naked eye. This is the first time such a curved display has been realized using such a simple setup (only a commercial projector and lens-array). The reconstructions are shown in Figure.7

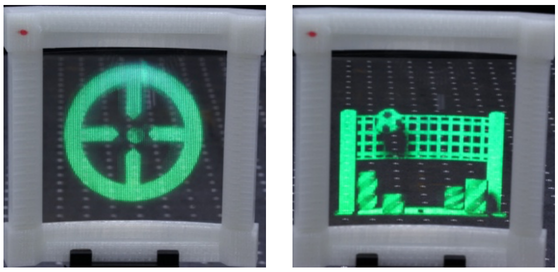
Figure 7. a) Reconstructed image before calibration, b) Reconstructed image after calibration using diffuse corners as markers.

Peer reviewed Journal Publications

1. Jorissen, L. Oi, R. Wakunami, K., Ichihashi, Y., Lafruit, G., Yamamoto, K., Bekaert, P., B J Jackin, Holographic Micromirror Array with Diffuse Areas for Accurate Calibration of 3D Light-Field Display. Appl. Sci, 10, 7188 (2020)

2. L Jorissen, B J Jackin, R Oi, K Wakunami, M Okui, Y Ichihashi, G Lafruit, K Yamamoto, and P Bekaert, "Homography based identification for automatic and robust calibration of projection integral imaging displays," Appl. Opt. 58, 1200-1209 (2019)

3. B J Jackin, L Jorissen, R Oi, J Y Wu, K Wakunami, M Okui, Y Ichihashi, P Bekaert, Y P Huang, and K Yamamoto, "Digitally designed holographic optical element for light field displays," Optics Letters 43, 3738-3741 (2018)

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　3件）

１．著者名 Jackin Boaz Jessie	４．巻 11305
２．論文標題 Digitally designed holographic optical elements for large-size light field displays	５．発行年 2020年
３．雑誌名 Proceedings Volume 11305, Ultra-High-Definition Imaging Systems III	６．最初と最後の頁 38 - 44
掲載論文のDOI（デジタルオブジェクト識別子） 10.1117/12.2550796	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Jackin Boaz Jessie、Jorissen Lode、Oi Ryutaro、Wu Jui Yi、Wakunami Koki、Okui Makoto、Ichihashi Yasuyuki、Bekaert Philippe、Huang Yi Pai、Yamamoto Kenji	４．巻 43
２．論文標題 Digitally designed holographic optical element for light field displays	５．発行年 2018年
３．雑誌名 Optics Letters	６．最初と最後の頁 3738～3738
掲載論文のDOI（デジタルオブジェクト識別子） 10.1364/OL.43.003738	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Jorissen Lode、Jackin Boaz Jessie、Oi Ryutaro、Wakunami Koki、Okui Makoto、Ichihashi Yasuyuki、Lafruit Gauthier、Yamamoto Kenji、Bekaert Philippe	４．巻 58
２．論文標題 Homography based identification for automatic and robust calibration of projection integral imaging displays	５．発行年 2019年
３．雑誌名 Applied Optics	６．最初と最後の頁 1200～1200
掲載論文のDOI（デジタルオブジェクト識別子） 10.1364/AO.58.001200	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計7件（うち招待講演　3件／うち国際学会　7件）

１．発表者名 Boaz Jessie Jackin
２．発表標題 Digitally designed holographic optical elements for large-size light field displays
３．学会等名 SPIE Photonics West - 2020, San Francisco, USA（招待講演）（国際学会）
４．発表年 2019年～2020年

1．発表者名 Boaz Jessie Jackin
2．発表標題 Large Size and See-Through Light Field Displays Using DDHOE
3．学会等名 International meeting on information displays - 2019, Gyeongju, Korea（招待講演）（国際学会）
4．発表年 2019年～2020年

1．発表者名 Boaz Jessie Jackin
2．発表標題 Integral imaging based large-size see-through head up display for AR applications using DDHOE and projector
3．学会等名 Optics and Photonics International Congress OPIE - 2019, Yokohama, Japan（招待講演）（国際学会）
4．発表年 2019年～2020年

1．発表者名 B J Jackin , L Jorissen , R Oi, K Wakunami , Y Ichihashi , M Okui , P Bekaert and K Yamamoto
2．発表標題 Digitally designed HOE lens arrays for large size see-through head up displays
3．学会等名 Frontiers in Optics - 2018 (Washington-DC, USA)（国際学会）
4．発表年 2018年

1．発表者名 Jackin B J , L Jorissen , R Oi , Y Ichihashi , K Wakunami , M Okui and K Yamamoto
2．発表標題 Projection type large-size integral imaging display without collimation optics using DDHOE
3．学会等名 3D Display and Applications - 2018 (Taipei, Taiwan)（国際学会）
4．発表年 2018年

1．発表者名 B J Jackin, L Jorissen, R Oi, K Wakunami, Y Ichihashi, M Okui, K Yamamoto
2．発表標題 Large-Size and See-Through Color Light Field Display Using Projector and DDHOE
3．学会等名 International Display Workshop - 2018 (Nagoya, Japan)（国際学会）
4．発表年 2018年

1．発表者名 B J Jackin, R Oi, K Wakunami, Y Ichihashi, O Makoto, K Yamamoto
2．発表標題 Digitally designed holographic optical element for large size see-through light field display
3．学会等名 Optics and Photonics Japan - 2018 (Tokyo, Japan)（国際学会）
4．発表年 2018年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関