

超広視野角ディスプレイによる眼の後方に形成される 空中像の両眼視差と形成位置

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あらまし 視野全体を画像でカバーする新しいディスプレイは、様々なアプリケーションにとって非常に魅力的である。本論文では、超広視野を実現するために、正常な収束側視差とは異なる視聴眼の後ろの航空画像を再構成することを提案する。空中ディスプレイには空中映像の周囲にハードウェアがないため、ディスプレイハードウェアと空中映像の間に目の後ろに形成された空中映像を観察することができる。我々は、再帰反射による空中イメージング(AIRR)を用いて、目を見るすぐ後ろの画像を生成するプロトタイプ空中ディスプレイを開発した。視野の背後で航空画像を再構成した場合でも、航空画像との絶対視差が発散した左右の反転画像が観察されることがある。さらに、提案手法は、画像で視野全体をカバーすることができる。

キーワード：空中ディスプレイ, aerial imaging by retro-reflection (AIRR), 両眼視差, 視野角

1. まえがき

浮動画像は物理的なスクリーンを使わずに空中に表示するため、空中ディスプレイはデジタルサイネージに広く利用されることが期待される。AIRR(Aerial Imaging by Retroreflection)は、航空画像を形成する方法であり¹⁾、これまでに開発された航空ディスプレイデバイスの多くは、航空深度融合3Dディスプレイ^{2,3)}や全方位航空ディスプレイ⁴⁾などの卓上サイズである。AIRRタブレットは、3D高速ハンドトラッキングをAIRRで形成された航空画像に統合したもので、航空ディスプレイを空中インターフェースとして利用することも実現されている⁵⁾。航空画像の明るさと解像度はAIRRの問題であるが、これらの問題をソフトウェア⁶⁾やハードウェア^{7,8)}の観点から解決する方法も提案されている。これらの研究は、ポップアップ距離の短いノートパソコンサイズの航空画像を用いているため、航空画像の位置を超えてビームスプリッターに近い観測は、多くの注意が必要であり、アプリケーションには適さない。

近年、AIRRを用いた没入型ライフサイズの空中ディスプレイにより、空撮画像とハードウェアの空間が広がり、モーションキャプチャが搭載され、インタラクティブなディスプレイが可能になった⁹⁻¹¹⁾。

また、フレネルレンズを用いて浮遊距離を長くした¹²⁾

。この没入型航空ディスプレイは、航空画像のポップアップ距離が大きく、航空画像の周りにハードウェアがないため、航空画像の閉じ方や横移動に注意を払う必要がない。情報画面に近づくと画像が大きくなり、視野全体を画像でカバーすることが知られているが、最も近い距離は我々の鼻によって制限される。しかし、航空ディスプレイには航空画像周辺にハードウェアがないため、航空ディスプレイはこのハードウェアの制限を克服し、目の後ろでも、見ている目だけの情報を提示する可能性がある。

空撮画像が頭の後方に形成されている場合、どのような画像が観察されますか?例えば、オブザーバーがディスプレイのハードウェアと空中映像の間に立っている場合、観測された空中映像は目の奥に形成されるが、日常生活では不可能である。この航空写真は、日次の収束側とは異なり、発散側の絶対視差を持つ。この観察方法は、航空ディスプレイの応用範囲を広げ、超広視野の可能性を秘めている。本研究の目的は、この観察方法を応用することで、フロントガラス全域をカバーする画像を提示できる、超広視野角のヘッドアップディスプレイを実現することである。

本研究の目的は、航空写真を視聴眼の後ろに再構成した場合、どのような画像が観察されるかを明らかにすることである。実体顕微鏡カメラ

Received June 21, 2024; Revised September 14, 2024; Accepted October 27, 2024

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Absolute Parallax and Reconstruction Position of Aerial Image Formed Just Behind Viewing Eyes in Ultra-Wide Field-of-View Display

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Abstract A novel display covering entire field of view with image is highly attractive for various application. This paper proposes to reconstruct an aerial image behind viewing eyes that are different from normal parallax of convergence side to realize ultra-wide field-of-view. As aerial display has no hardware around aerial image, we can observe aerial image formed behind the eyes between the display hardware and aerial image. We have developed a prototype aerial display to form an image just behind viewing eyes using aerial imaging by retro-reflection (AIRR). Even when aerial image is reconstructed behind viewing eyes, left and right reversed image with diverged absolute parallax to aerial image can be observed. Furthermore, our proposed method can cover entire field of view with images.

Keywords: Aerial display, aerial imaging by retro-reflection (AIRR), binocular disparity, field-of-view.

1. Introduction

Aerial display is expected to be widely used for digital signage because a floating image is displayed in mid-air without a physical screen. Aerial imaging by retro-reflection (AIRR) is a method of forming an aerial image¹⁾ and many of the aerial display devices developed so far have been tabletop size, such as aerial depth-fused 3D display^{2, 3)} and omnidirectional aerial display⁴⁾. The AIRR tablet, where the 3D high-speed hand tracking was integrated into the aerial image formed by AIRR, has also been realized to use aerial display as aerial interface⁵⁾. Brightness and resolution of aerial image are problems for AIRR, but methods to solve these problems in terms of software⁶⁾ or hardware^{7, 8)} have also been proposed. Since these studies use laptop-sized aerial images with a short pop-up distance, observations beyond the aerial image position and closer to the beam splitter needs much attention and is not suitable for applications.

Recently, an immersive life-size aerial display based on AIRR has increased the space between the aerial image and the hardware, which is equipped with motion capture and enables interactive display⁹⁻¹¹⁾ and the use

of Fresnel lenses to increase the floating distance¹²⁾. This immersive aerial display has no need to pay much attention for closing or moving beyond aerial images, because this can provide large pop-up distance of aerial image and no hardware around aerial image. Although it is known that getting closer to the information screen makes images larger and covering the entire field of view with images, the closest distance is limited by our nose. However, aerial display overcome this hardware limitation and has a possibility to present information just around the viewing eyes, even behind eyes, because aerial display has no hardware around the aerial image.

What kind of images would you observe when the aerial image is formed behind your head? For example, when observer stands between the display hardware and the aerial image, observed aerial image formed just behind the eyes, which is not possible in daily life. This aerial image has absolute parallax of a divergence side unlike the daily convergence side. This observation method expands the range of applications for aerial displays and has possibilities for ultra-wide field-of-view. Our aim of study is to realize a head-up display with an ultra-wide field-of-viewing angle that can present images covering the entire windshield area by applying this observation method.

The purpose of this study is to determine what kind of image can be observed when the aerial image is reconstructed behind viewing eyes. Stereoscopic cameras

Received June 21, 2024; Revised September 14, 2024; Accepted October 27, 2024

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は、航空画像を撮影するために使用され、観察者の背後に形成された航空画像が観察できることを明確にする。

2. AIRR(Aerial Imaging by RetroReflection)による超広視野ディスプレイ

2.1 AIRRの原理

レトロ反射による空中撮像(AIRR)の原理を図1に示す。AIRRは光源、ビームスプリッター、レトロ反射器から構成される。光源から放出された光はビームスプリッターに送られ、反射光と透過光に分割される。反射光はレトロ反射器に送られ、再びレトロ反射によってビームスプリッターに戻る。次に、ビームスプリッターを透過した光は、ビームスプリッターに対して光源と対称な位置に集光され、航空画像を形成する。

2.2 空中画像を用いた超広視野ディスプレイの原理

超広視野ディスプレイの原理を図2に示す。図2(a)のように、通常視聴の航空画像であれば、ハードウェアと観察者の間に浮いている航空画像が見える。図2(b)に示すように、空中画像の超広視野の場合、観察者のすぐ後ろに空中画像が再構成される。このような状況は日常生活では不可能である。絶対視差で収束側を強調した通常の視聴では、航空写真の左端の光線(青い線)が網膜の右側に現れる。一方、絶対視差の乖離側を持つ超広視野では、網膜の左側に現れる。これは、垂直方向と水平方向に反転した画像と発散した画像を観察することにつながる。網膜上の画像サイズが超大型化し、両目の視覚軸が平行に発散する。

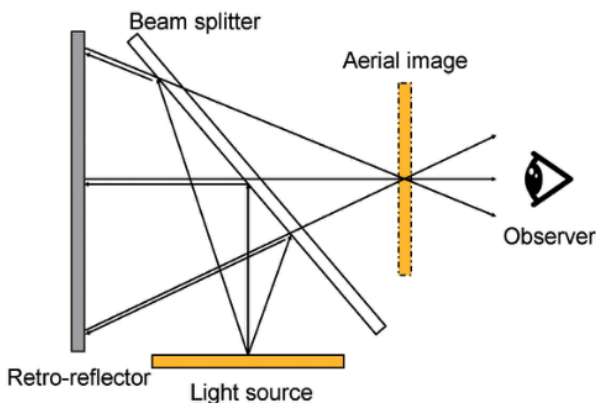


図1 レトロ反射による空中撮像(AIRR)の原理。

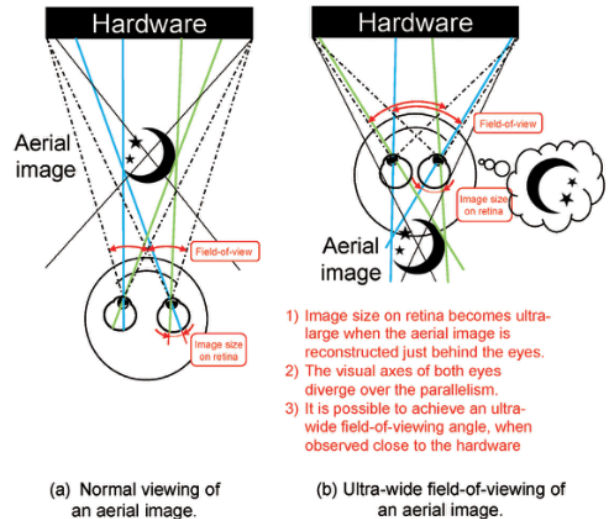


図2 航空画像を用いた超広視野ディスプレイの原理。

さらに、空中ディスプレイからの光はハードウェアから後方の観察者に収束するため、ハードウェアの近くに観察すると収束した光の角度が広くなり、超広視野角を達成することが可能になる。例えば、超没入型視聴は、通常の視聴の約3倍の視野¹³⁾を生成する。

3. 両眼視差の測定と視聴位置からの再構成画像距離の測定

3.1 実験方法

本研究で使用した光学系を図3に示す。開発したディスプレイはAIRRをベースにしている。プロトタイプは、フラットパネルディスプレイ(FPD)、ビームスプリッター、レトロリフレクターで構成されている。航空画像の位置は、ビームスプリッターに対する光源ディスプレイの平面对称性であった。図1とは異なり、シースルー構造である。空中で航空画像が形成された。表示画像とその航空写真を図4と図5に示す。大きな画像は希望する航空写真であり、小さな画像は再帰反射による望ましくない反射である。立体カメラ(FUJI FILM: FINEPIX REAL 3D W1)を用いて、視聴位置を+400mmから-300mmに変更し、空撮画像を撮影した。両レンズのベースライン長は77mm、焦点距離は6.3mm、イメージセンサーサイズは6.2mm×4.7mmであった。キャプチャ画像サイズは2048ピクセル×1536ピクセル。立体視画像から両眼視差を算出した。両眼視差は次式で表される。

$$D = \frac{x}{s} \times L \quad (1)$$

is used to capture aerial images, which clarifies that the aerial image formed behind the observer can be observed.

2. Ultra-wide field-of-view display using AIRR (Aerial Imaging by Retro-Reflection)

2.1 Principle of AIRR

Principle of aerial imaging by retro-reflection (AIRR) is shown in Fig. 1. AIRR consists of a light source, a beam splitter and a retro-reflector. The light emitted from the light source goes to the beam splitter and is split into reflected and transmitted light. The reflected light goes to the retro-reflector and returns to the beam splitter again by retro-reflection. Then the light transmitted through the beam splitter is focused on a position symmetrical to the light source with respect to the beam splitter to form an aerial image.

2.2 Principle of ultra-wide field-of-view display using aerial image

Principle of ultra-wide field-of-view display is shown in Fig. 2. In the case of normal viewing of an aerial image as shown in Fig. 2(a), the aerial image floating between the hardware and the observer can be seen. In the case of ultra-wide field-of-viewing of an aerial image as shown in Fig. 2(b), an aerial image is reconstructed just behind the observer. This situation is not possible in daily life. In normal viewing with convergence side in absolute parallax, the left-end rays (blue lines) of the aerial image appears on the right side of the retina. On the other hand, in ultra-wide field-of-viewing with divergence side in absolute parallax, it appears on the left side of the retina. This leads to observation of an inverted and diverged image vertically and horizontally. Its image size on retina become ultra large and the visual axes of both eyes diverge over the parallelism.

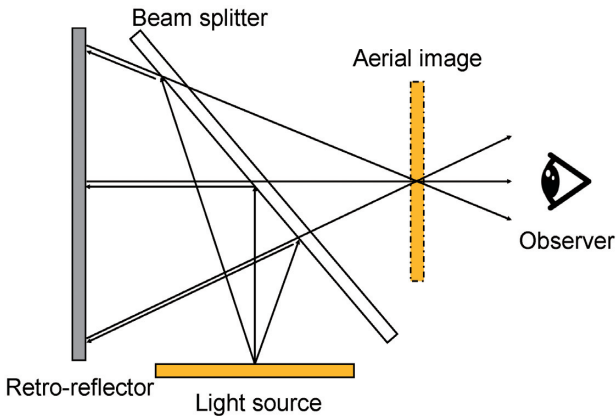


Fig. 1 Principle of Aerial Imaging by Retro-Reflection (AIRR).

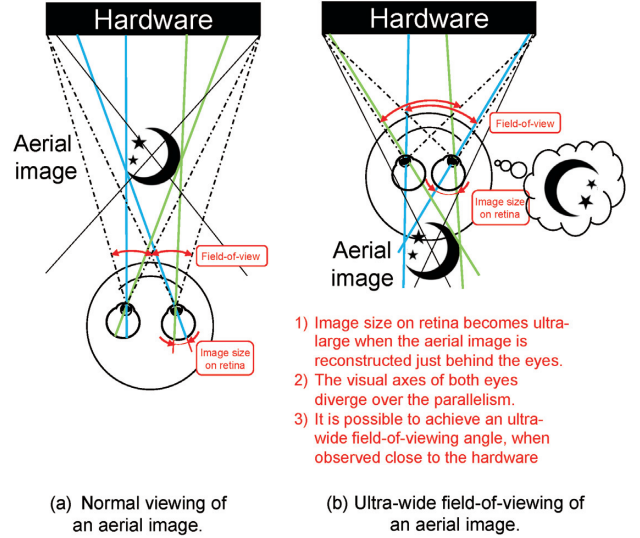


Fig. 2 Principle of ultra-wide field-of-view display using aerial image.

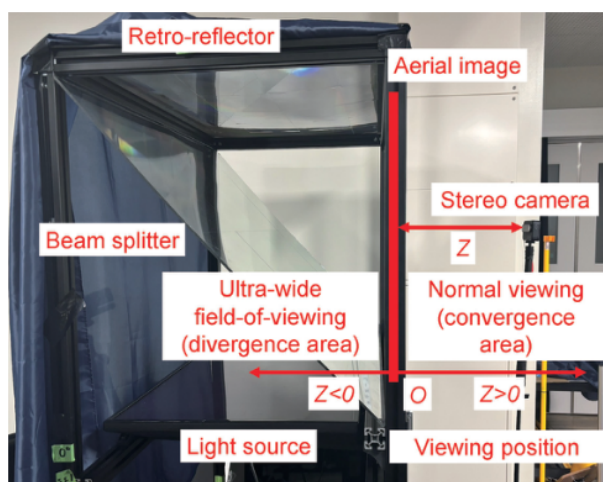
Moreover, since the lights from aerial display are converged from the hardware to behind observer, converged angle of lights is wider when observed close to the hardware, making it possible to achieve an ultra-wide field-of-viewing angle. For example, ultra-immersive viewing produces a field-of-view about 3 times that of the normal viewing¹³⁾.

3. Measurement of binocular disparity and reconstructed image distance from viewing position

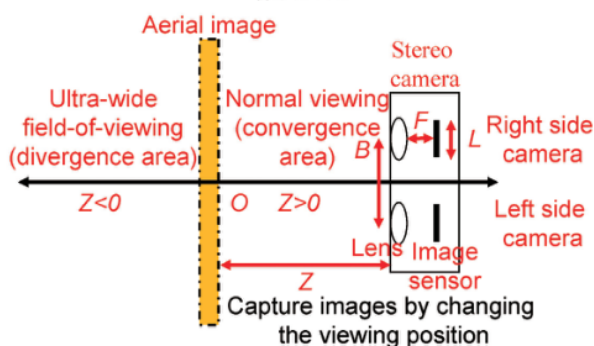
3.1 Experimental method

The optical system used in this study is shown in Fig. 3. The developed display was based on AIRR. Our prototype consisted of a flat-panel display (FPD), a beam splitter, and a retro-reflector. The position of the aerial image was in plane symmetry of the light source display with respect to the beam splitter. Unlike Fig. 1, it is see-through structure. Aerial images were formed in mid-air. Displayed image and its aerial image are shown in Fig. 4 and 5. The large image was a desired aerial image, and the small image was an undesired reflection by retro-reflector. Stereoscopic cameras (FUJI FILM: FINEPIX REAL 3D W1) was used to capture the aerial images by changing the viewing position from +400 mm to -300 mm. The baseline length of both lenses was 77 mm, focal length was 6.3 mm and image sensor size was 6.2 mm × 4.7 mm. Captured image size was 2048 pixels × 1536 pixels. Binocular disparity was calculated from the stereoscopic images. Binocular disparity was expressed by

$$D = \frac{x}{s} \times L \quad (1)$$



(a) Side view.



(b) Top view.

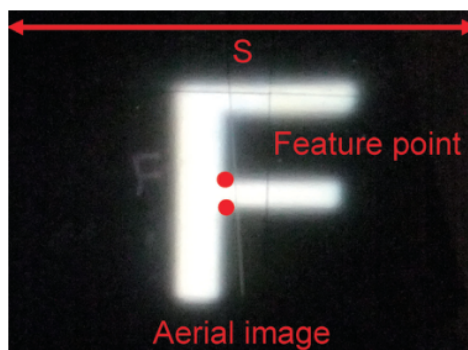
図3 光学系を用いたAIRR(a) 側面図、(b) 上面図。
 Z は、視聴位置からの航空写真の距離である。超広視野($Z < 0$)では、絶対視差の発散側である。



図4 FPDの表示画像

ここで、 D は両眼視差、 S は水平方向の撮影画像サイズ(2048ピクセル)、 L は水平方向の画像センサーサイズ(6.2mm)である。 x は、図5に示すように、立体画像中の2つの特徴点について、左右の画像間の画素移動の平均値である。視聴位置からの画像距離は次式で表される。

$$Z = \frac{B \times F}{D} \quad (2)$$



(The small image is a reflection by retro-reflector)

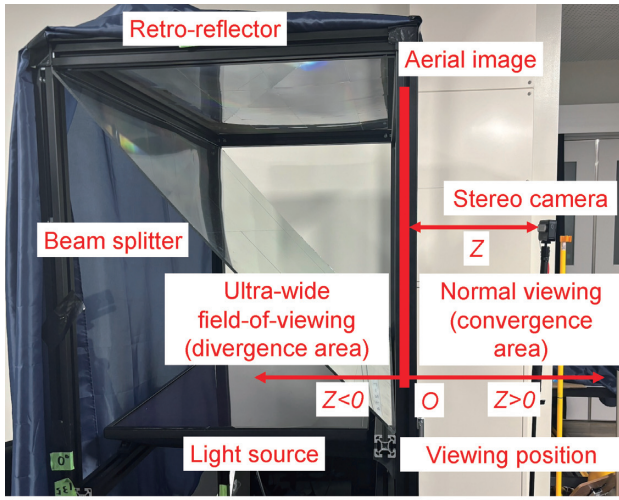
図5 カメラで撮影した航空写真。大きな画像は希望する航空写真で、小さな画像はレトロリフレクターによる望ましくない反射であった。両眼視差の算出には、2つの特徴点を使用した。

ここで、 Z は視聴位置からの画像距離、 B は両レンズのベースライン長、 F は焦点距離である。3.2 視聴位置からの再構成画像距離と両眼視差の理論値

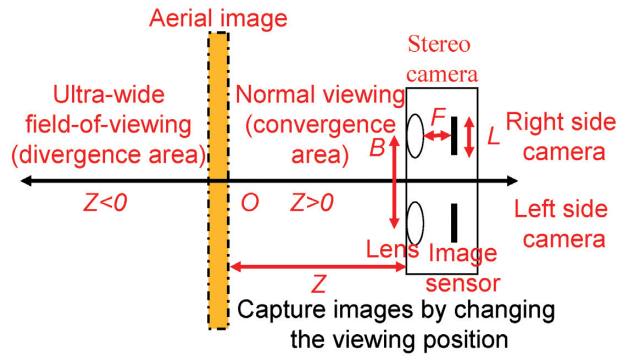
本実験で得られる再構成画像位置からの距離と両眼視差の理論値は、日常生活では不可能な、見る目の後ろに形成された画像の観察のため、図3(b)のように算出される。視聴位置は航空画像の位置に基づいているため、視聴位置と視聴位置からの画像距離は等しい。また、視聴位置からの画像距離と両眼視差の関係は式2のようになる。超広視野($Z < 0$)では、絶対視差において、日次の収束側とは異なり、発散側となる。 $Z < 0$ のとき、 $B < 0$ かつ $F < 0$ なので、負の両眼視差が再現される。負の両眼視差は絶対視差の発散側を示し、左右の画像は反転して発散する。

4. 両眼視差と視聴位置からの画像再構成距離の結果

図6は、立体カメラで撮影された航空写真で、航空写真位置から(a)-300mm、(b)-200mm、(c)+200mm、(d)+400mmの位置にある。図6(a)と(b)は、航空画像の超広視野のネガティブな視野位置、すなわち異常な視野位置で撮影された航空画像である。航空画像位置からの絶対視聴距離が長くなるにつれて、画像の大きさは小さくなる。



(a) Side view.



(b) Top view.

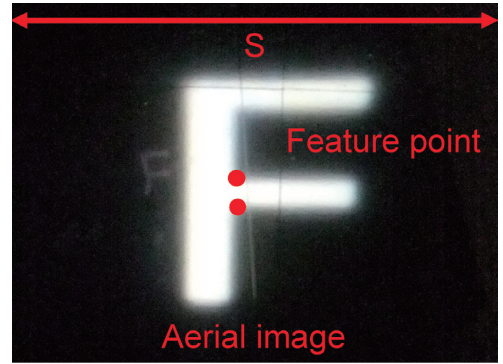
Fig. 3 Our optical system based AIRR. (a) Side view and (b) top view. Z is the aerial image distance from viewing position. In ultra-wide field-of-viewing ($Z < 0$), it is a divergence side in absolute parallax.



Fig. 4 Displayed image on FPD.

where D was binocular disparity, S was horizontal captured image size (2048 pixel), L was horizontal image sensor size (6.2 mm). x was the average of the pixel shift between the left and right images for the two feature points in the stereoscopic image as shown in Fig. 5. The image distance from viewing position was expressed by

$$Z = \frac{B \times F}{D} \quad (2)$$



(The small image is a reflection by retro-reflector)

Fig. 5 Aerial image taken by camera. The large image was a desired aerial image and the small image was an undesired reflection by retro-reflector. Two feature points were used for calculating binocular disparity.

where Z was the image distance from viewing position, B was baseline length of both lenses and F was focal length.

3.2 Theoretical values of reconstructed image distance from viewing position and binocular disparity

The theoretical values of reconstructed image distance from viewing position and binocular disparity to be obtained in this experiment are calculated in Fig. 3(b), because of the observation of images formed behind the viewing eyes, which is not possible in daily life. Since the viewing position is based on the aerial image position, the viewing position and the image distance from viewing position are equal. In addition, the relationship between the image distance from viewing position and binocular disparity is as in Equation 2. In ultra-wide field-of-viewing ($Z < 0$), it is a divergence side in absolute parallax, unlike the daily convergence side. When $Z < 0$, negative binocular disparity is reproduced because $B < 0$ and $F < 0$. Negative binocular disparity indicates divergence side in absolute parallax, left and right images are inverted and diverged.

4. Results of binocular disparity and reconstructed image distance from viewing position

Figure 6 shows the aerial images captured by stereoscopic cameras at (a) -300 mm, (b) -200 mm, (c) +200 mm and (d) +400 mm from aerial image position. Figure 6(a) and 6(b) show aerial images captured at negative viewing position of ultra-wide field-of-viewing of an aerial image, i.e. in an unusual viewing position. The size of the image decreases as the absolute viewing distance from the aerial image position increases.

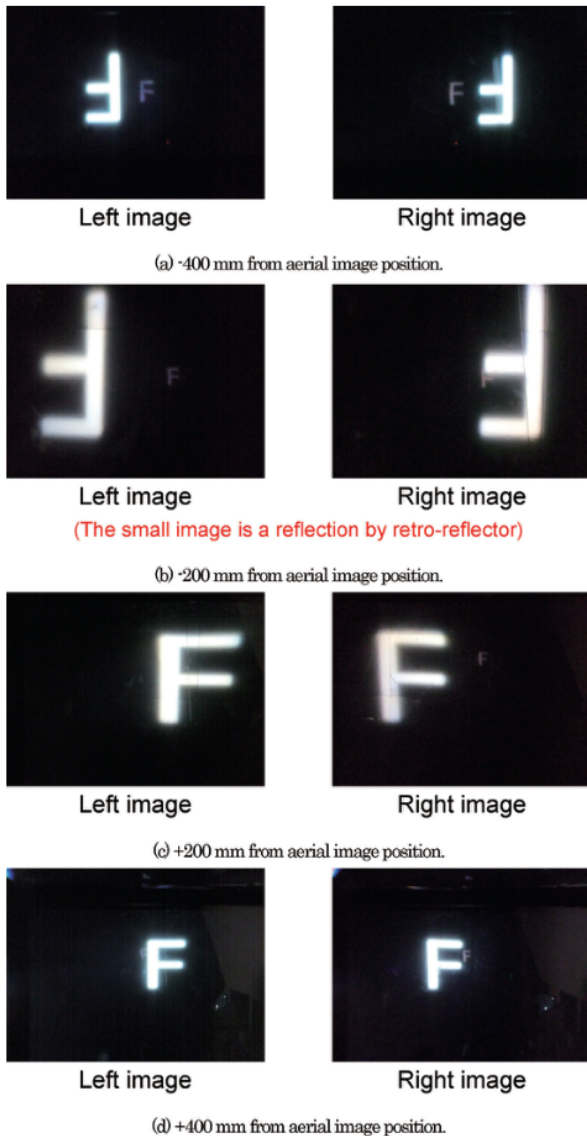


図6 立体カメラで撮影された航空写真(航空写真位置から(a)-300mm、(b)-200mm、(c)+200mm、(d)+400mm)。(a)と(b)では、空中画像の超広視野のネガティブな視野位置、すなわち異常な視野位置で撮影された空中画像。(c)と(d)では、通常画像の正視位置における従来の航空画像。

さらに、図6(c)、(d)に示すように、立体視画像の左画像と右画像を通常の立体視画像に対して反転させる。逆に、図6(c)、(d)に示すように、通常画像の正視位置にある従来の航空画像では、観察者が画像に近ければ近いほど、画像サイズが大きくなる。提案手法により、目の後ろに再構成された航空画像を観察することが可能となり、画像で全視野をカバーする超広視野を実現することが可能となった。また、画像サイズは航空写真の位置に近いほど大きくなり、視聴直後に形成されるのであれば

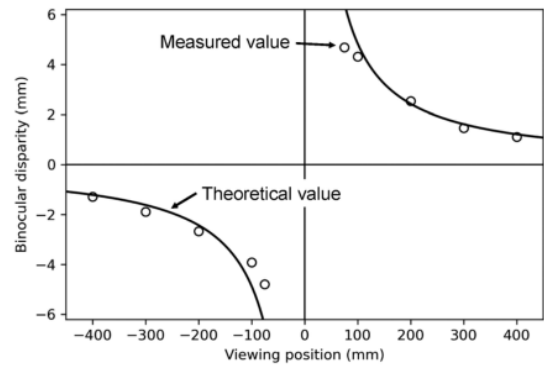


図7 実測された両眼視差と理論上の両眼視差。横軸は航空写真から見た位置である。縦軸の負の値は絶対視差の発散側を示し、左右の画像は反転して発散している。

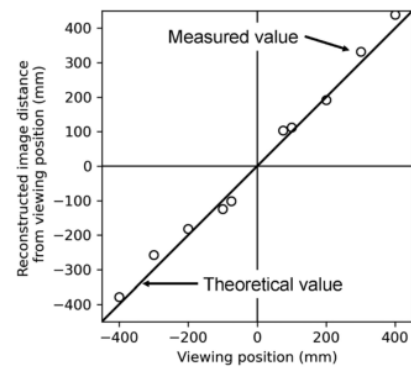


図8 視聴位置から再構成された画像距離横軸は航空写真から見た位置である。縦軸は、両眼視差で計算することにより、視位置からの画像距離を再構成したものである。縦軸の負の値は、ステレオカメラの後ろに航空画像が形成されていることを意味する。

目、画像サイズが超大型である。

実測された両眼視差と理論上の両眼視差を図7に示す。正視位置からゼロまで航空画像平面に近いほど、正の両眼視差は大きくなり、航空画像平面では無限に正に発散する。一方、視聴位置がゼロの航空画像位置を通過して負になると、両眼視差は反転し、負の無限大から負になる。両眼視差がマイナスの場合は、絶対視差で発散側を示し、左右の画像は反転して両眼で発散しており、日常的な観察では珍しいことである。図8は、視聴位置からの画像距離を再構成した結果である。正視聴位置では、ステレオカメラの前で航空画像が再構成されるが、負視聴位置では、ステレオカメラの後方にあると再構成された航空画像の位置が計算される。

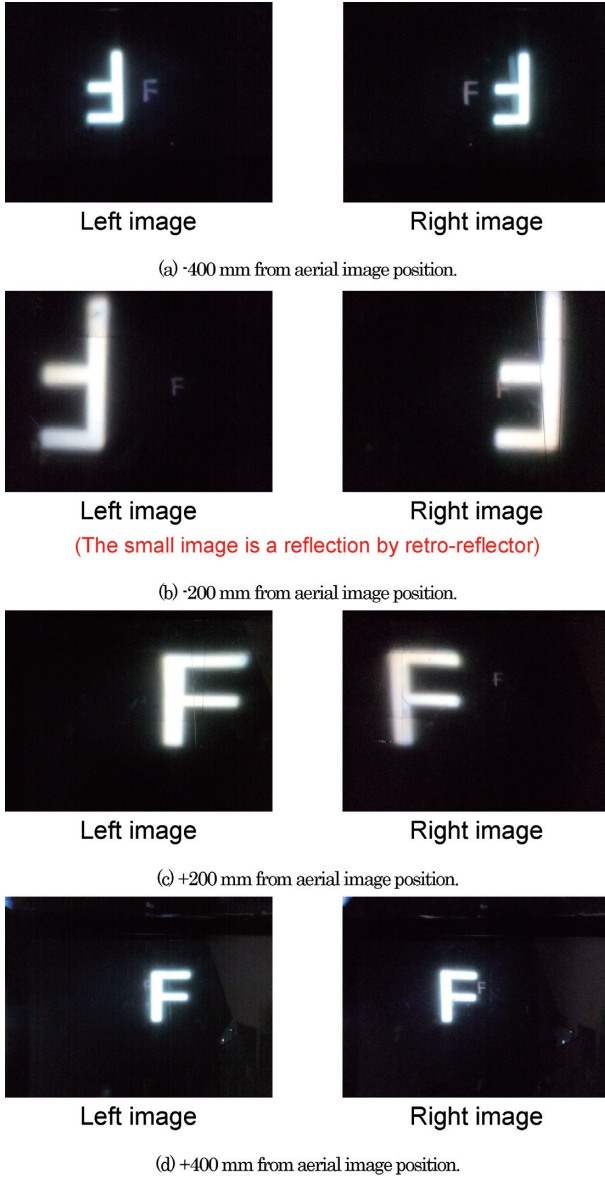


Fig. 6 Aerial images captured by stereoscopic cameras at (a) -300 mm, (b) -200 mm, (c) +200 mm and (d) +400 mm from aerial image position. At (a) and (b), aerial images captured at negative viewing position of ultra-wide field-of-viewing of an aerial image, i.e. in an unusual viewing position. At (c) and (d), conventional aerial image at positive viewing position of the normal image.

Moreover, the left image and right image of the stereoscopic images are reversed against the normal stereoscopic images as shown in Fig. 6(c) and 6(d). On the contrary, in conventional aerial image at positive viewing position of the normal image as shown in Fig. 6(c) and 6(d), the closer the observer gets to the image, the larger the image size becomes. With our proposed method, it is possible to observe the aerial image reconstructed behind the eyes and to realize ultra-wide field-of-view that cover entire field of view with images. Also, the image size is larger the closer to the aerial image position, and if it is formed just around viewing

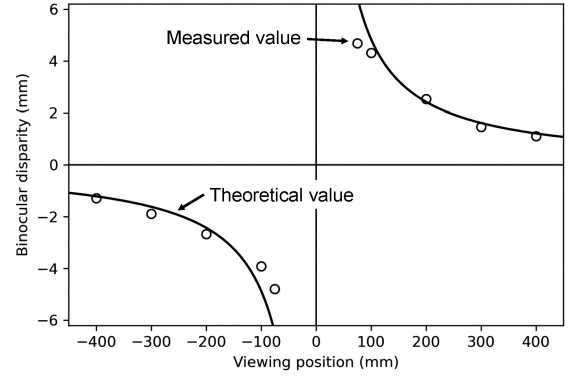


Fig. 7 Measured binocular disparity and theoretical binocular disparity. Horizontal axis is viewing position from the aerial image. Negative values on the vertical axis indicates divergence side in absolute parallax, left and right images are inverted and diverged.

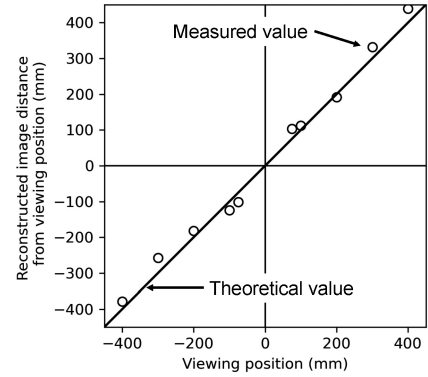


Fig. 8 Reconstructed image distances from viewing position. Horizontal axis is viewing position from the aerial image. Vertical axis is reconstructed image distance from viewing position by calculating with binocular disparity. Negative value on vertical axis means that aerial image is formed behind stereo camera.

eyes, image size is ultra large.

Measured binocular disparity and theoretical binocular disparity are shown in Fig. 7. The closer to aerial image plane from positive viewing position to zero, the larger positive binocular disparity becomes, and is diverged to positive infinitely at the aerial image plane. On the other hand, when viewing position pass through the aerial image position of zero and become negative, the binocular disparity reverses and becomes negative from negative infinity. Negative binocular disparity indicates divergence side in absolute parallax, left and right images are inverted and diverged for both eyes, which is unusual in everyday observations. Figure 8 shows result of reconstructed image distance from viewing position. In positive viewing position, the aerial image is reconstructed in front of the stereo camera, but in negative viewing position, the reconstructed position of aerial image is calculated to be behind the stereo camera.

5. 議論

図6では、画像サイズが空撮画像位置に近いほど大きくなっている。したがって、通常視聴時よりも小さな表示画像で、超広視野角を達成することができる。また、AIRRの視野はビームスプリッタとレトロリフレクターのサイズに依存するため、より小さな表示画像を使用しても影響されない。したがって、小さな光源でも超広視野を実現することができる。次に、小さなディスプレイ画像を使用することにより、航空画像のぼやけの影響は大きくなるが、ボールレンズを仮想共役位置に配置する高解像度技術を使用することで、これを改善することができる¹⁴⁾。視聴位置の絶対値が小さいと、実測値と理論値の誤差が大きくなる。撮像面に近い位置にあるため、測定誤差やカメラの収差の影響と考えられる。

図7において、観察者の背後に形成された航空画像を観察すると、左右の画像が反転して発散しており、日常生活では不可能である。両目で観察すると、表示される画像は二重に見える。したがって、左目と右目にそれぞれ表示される画像を準備する必要がある。例えば、アナグリフ画像を用いることで、通常の観察と同じように画像を観察することができる¹⁵⁾。したがって、立体視技術は二重画像の問題を解決できると考えられる。

6. むすび

本論文では、超広視野を実現するために、目のすぐ後ろの航空画像を再構成する新しいディスプレイを提案した。我々は、再帰反射による空中イメージング(AIRR)を用いて、目のすぐ後ろの画像を生成するプロトタイプ空中ディスプレイを開発した。航空画像を視眼の後ろに再構成しても、絶対視差が発散した左右の反転画像が観察されることがある。さらに、提案手法は、画像で視野全体をカバーすることができる。この方法は、没入型ディスプレイのような航空ディスプレイの新しい可能性に有望である。

超広視野での感覚を実現する。

本研究の一部は、日本学術振興会科研費 19H04155, 20H05702 の助成を受けた。

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5. Discussion

In Fig. 6, the image size is larger the closer to the aerial image position. Therefore, a ultra-wide field-of-viewing angle can be achieved with a smaller displayed image than in normal viewing. Also, since the field-of-view of AIRR depends on the size of the beam splitter and retro-reflector, it is not influenced by using a smaller display image. Therefore, even a small light source can achieve an ultra-wide field-of-viewing. Next, the influence of blurring of the aerial image increases due to the use of a small display image, but this can be improved by using a high-resolution technique in which the ball lens is placed at the virtual conjugate position¹⁴⁾. The error between measured and theoretical values becomes large when the absolute value of the viewing position is small. Because of its position close to the imaging plane, it is considered to be an influence of measurement error and camera aberration

In Fig. 7, when the aerial image formed behind the observer is observed, the left and right images are inverted and diverged, which is not possible in everyday life. When the image is observed with both eyes, the displayed image appears double. Therefore, it is necessary to prepare images to be shown to the left and right eyes, respectively. For example, by using anaglyph images, we can observe images in the same way as normal observation¹⁵⁾. Thus, we believe that stereoscopic technology can solve the problem of double images.

6. Conclusion

This paper proposed a novel display that reconstructs an aerial image just behind viewing eyes to realize ultra-wide field-of-view. We have developed a prototype aerial display to form an image just behind viewing eyes by using aerial imaging by retro-reflection (AIRR). Even when the aerial image is reconstructed behind viewing eyes, left and right reversed image with diverged absolute parallax can be observed. Furthermore, our proposed method can cover entire field of view with images. This method is promising for new possibilities for aerial displays, such as one providing an immersive

sensation with ultra-wide field-of-view.

A part of research was supported by JSPS KAKENHI Grant Numbers 19H04155, 20H05702.

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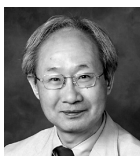
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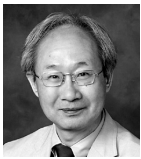
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