Inverse conversion algorithm for an all-optical depth coloring camera

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Three-dimensional (3D) metrology has received a lot of attention from academic and industrial communities due to its broad applications, such as 3D contents, 3D printing, and autonomous driving. The all-optical depth coloring (AODC) camera has some benefits in computation load since it extracts depth information of an object fully optically. The AODC camera represents the depth of the object as a variation of wavelength, and spectroscopy is generally required to measure the wavelength. However, in the AODC camera, the color vector in RGB color space is convertible inversely into the wavelength after projection on the normalized rgb plane because the detected spectrum through the gating part has a narrow bandwidth as a result of the width of the slit in the projection part. In this paper, we propose an inverse conversion algorithm from RGB color to depth without spectroscopy. Experimental results are presented to confirm its feasibility. Also, some practical limitations are discussed, resulting from the nonlinearity of the response of the image sensor and the widths of the slits in the projection part and the gating part.

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1. INTRODUCTION

Three-dimensional (3D) metrological techniques have been developed, and these techniques are a vital element for 3D modeling and object recognition [1–4]. Among them, noncontact depth extraction techniques have obvious advantages because these techniques can extract the depth information of objects nondestructively [5–7]. One of the most representative techniques is a structured illumination (SI) method [8–10]. The SI method measures distortion of patterns after specific patterns are illuminated on objects, and then the depth information of the object is calculated from the amount of this distortion. Usually, computation is essential in order to extract the depth information from the distortion of patterns. However, the all-optical depth coloring (AODC) technique does not need any computation load since objects are fully optically colored by a rainbow spectrum according to their depth [11].

The AODC system converts depth information \( z \) into wavelengths \( \lambda \). That is, the wavelength map is provided in the AODC camera where the wavelength is directly related to the depth information. This wavelength map can be watched by the observer with bare eyes, but the recording of this wavelength map is difficult since the 3D hyperspectral cube needs to be measured in real time. There are several candidates for this purpose, such as hyperspectral imaging (HSI) and coded aperture spectral imaging (CASI).

Some HSI cameras take a snapshot of the 3D hyperspectral information, but it is difficult to implement both spatial and spectral resolutions sufficiently high, resulting from the limitations of the hardware design of the image sensor [12–14]. In the AODC method, the resolution of wavelength is directly related to the depth resolution and the spatial resolution is also important for recognizing the object. Thus, the snapshot HSI is improper for the AODC application for measuring high-resolution images.

CASI is an alternative way to measure the 3D hyperspectral cube in real time by using a coded aperture, dispersive elements, and a two-dimensional (2D) image sensor [15–17]. In CASI, the measured optical field is modulated by the dispersive elements and the coded aperture. A coded image of the 3D hyperspectral cube \((x, y, \lambda)\) is captured by the 2D image sensor and the captured image is processed for recovering the 3D hyperspectral cube. However, the wavelength map measured by the AODC camera is intrinsically different from the hyperspectral cube by the HSI. In the AODC camera, the whole space in the 3D cube is not concerned and only 2D surface information is acquired.

In this paper, we propose an inverse conversion method of RGB color into the depth for the AODC camera. The AODC camera extracts 2D depth information from the 2D surface in the 3D hyperspectral cube. The HSI camera measures the...
whole space in the 3D hyperspectral cube. It means that one point on the object can have an optical broad spectrum. However, the AODC camera records a single wavelength at one point. Hence, the measurement is regarded as only 2D information. This property originates from the fact that depth information is also a 2D surface of the objects. This fact gives us significant intuition in converting RGB color into depth inversely.

In a previous study [11], spectroscopy is essential in measuring the wavelength and the depth information is computed from the measured wavelength. In this paper, a traditional image sensor with an RGB color filter is applied to the AODC camera. From RGB color information, the wavelength is estimated and the depth is converted from it. In general, it is impossible to estimate the optical spectrum from RGB color. However, with the AODC camera, the estimation is feasible since RGB color is obtained from a single wavelength instead of a broad spectrum. The proposed inverse conversion algorithm brings about several practical benefits owing to the usage of an RGB image sensor. The RGB image sensor usually has an advantage in the cost, and it has relatively large spatial resolution in comparison with the sensor for HSI.

The RGB color measured by the RGB image sensor needs to be assigned to a wavelength inversely based on colorimetry. Colorimetry is to integrate the properties of human color vision systems into the measurement and the numerical specification of visible light [18,19]. Historically, the colorimetry originates from the International Commission on Illumination to define the standard observer colorimetry system and is called CIE colorimetry [20]. The colorimetry defines colors by the combination of three monochromatic primaries (red, green, and blue), and it also defines the functions of RGB coordinates according to wavelength. Thus, the wavelengths are converted to RGB colors depending on the specific environment [21–23].

This paper shows an inverse conversion method of RGB color into the depth for the AODC camera. In Section 2, the relation between depth and wavelength is explained. In Section 3, the reconstruction method the AODC camera is described by using the colorimetry. In Section 4, some experiments are demonstrated to prove the feasibility of the proposed method.

2. RELATION BETWEEN DEPTH AND WAVELENGTH IN THE AODC CAMERA

The AODC camera colors a rainbow pattern on objects according to their depth. The camera is based on directional gating, and the directional gating means that it accepts optical rays along a specific direction selectively. This method is achieved by mechanical slits and an imaging lens, and the acceptance of optical rays is determined by each position of the slit.

Figure 1(a) shows the AODC camera composed of a projection part and a gating part. The slit is positioned on the image plane of the lens in each part. The slit in the projection part has a vertical line shape. After white light passes through this slit, the vertical-line-shaped white light is changed into a rainbow pattern after passing through a grating. Then the rainbow pattern is illuminated on objects by the projection lens, and the propagation direction of the rainbow pattern is determined by the position of the slit opening. Thus, the direction of the rainbow pattern is changed accordingly as the slit moves from side to side. In the gating part, the slit functions as a filter for selecting the specific depth information of the object by the directional gating method. The optical encoder and decoder are performed by the projection part and the gating part, respectively.

In our experiment, two slits move reciprocally at three turns per second and the interested region is scanned six times for a second. The image sensor works synchronously with the movement of the slits, and its exposure time is set as 0.5 s. Hence, a single shot is an average of three scans. These parameters are chosen to obtain sufficient light intensity and reduce the noise by averaging.

In the projection part, the encoding process is implemented by swishing the illumination of the rainbow pattern on the object. In the gating part, the decoding process colors each point of the objects according to their depth due to the directional gating. Two slits in the projection part and the gating part are linked together and synchronized with each other. Thus, the angles of the ray projected on the object θL and the angle of the ray received by the gate θC are constrained to each other, and the sum of these two angles remains constant. In this configuration, the trajectory of the intersection point of the projection line and the gating line becomes a circle. The circle is
called a depth circle since every point on a depth circle with a fixed radius is colored by the same wavelength. For a given wavelength $\lambda$, the depth circle and its radius $r_{d}$ are defined as

$$
(y - 0.5g)^2 + \left( z - 0.5\sqrt{4r_{d}^2 - g^2} \right)^2 = r_{d}^2, \quad (1a)
$$

$$
r_{d} = \frac{g}{2\sin[\phi_k + \theta_j - \sin^{-1}(\lambda/d - \sin \theta_j)]}. \quad (1b)
$$

Here, $g$ is a gap between two reference points of the projection part and the gating part, and $\theta_j$ is an incident angle on the grating. $\phi_k$ is a bias angle, and it is determined by the distance between two slits. In our setup, only the first order of diffraction is considered and the radius of the depth circle depends on the wavelength, as shown in Fig. 1(b). The farther the object is from the AODC camera, the shorter wavelength is colored on the object. Therefore, the depth information is distinguishable by color and the whole process is done in an all optical way.

Both the projection lens and the camera lens capture the perspective scene, and the magnification of an object changes depending on its depth. In other words, the transverse length in the $x$ or $y$ direction is not independent of the longitudinal depth in the $z$ direction. Therefore, in order to obtain the precise position of the object, the fields of view (FOVs) of the projection lens and the camera lens need to be considered. Figure 2 shows the geometry to assign a position in space with a fixed depth $z$ into a pixel of the image sensor. $m$ and $n$ represent the number of pixels in the horizontal direction and the vertical direction, respectively. Each position $p_{ij}$ is captured by the pixel with $i$th order in the horizontal direction and $j$th order in the vertical direction at the image sensor. The straight line passing the position $(x, y, z)$ and the reference point of the camera $(0, 0, 0)$ is determined by

$$
\frac{x}{\tan \alpha} = \frac{y}{\tan \beta} = z, \quad (2)
$$

where $\alpha$ and $\beta$ are vertical and horizontal angles between the straight line and the $z$ axis, respectively.

$$
\alpha = \tan^{-1}\left(\frac{j - j_c}{m\tan(0.5\theta_{FOVy})}\right), \quad (3a)
$$

$$
\beta = \tan^{-1}\left(\frac{i_i - i}{n\tan(0.5\theta_{FOVx})}\right). \quad (3b)
$$

Here, $i$ and $j$ are the orders of the pixel at the center of the image sensor, $\theta_{FOVx}$ and $\theta_{FOVy}$ are the FOVs of the imaging lens in the $x$ and $y$ directions, respectively. From Eqs. (1a) and (2), the point $(x, y, z)$ captured at the pixel $(i, j)$ is specified for a given wavelength $\lambda$ and it is represented as

$$
x = \frac{m}{\tan \alpha} \left(\sqrt{4r_{d}^2 - g^2} + g \tan \beta \right)/\tan^2 \beta + 1, \quad (4a)
$$

$$
y = \frac{n}{\tan \beta} \left(\sqrt{4r_{d}^2 - g^2} + g \tan \alpha \right)/\tan^2 \alpha + 1, \quad (4b)
$$

$$
z = \sqrt{4r_{d}^2 - g^2} + g \tan \beta \right)/\tan^2 \beta + 1. \quad (4c)
$$

In the Eqs. (4a)–(4c), the position of the point depends on the wavelength since the radius of the depth circle $r_{d}$ is a function of the wavelength.

Figure 3 shows how the objects with three different depths are colored with three corresponding wavelengths. Here, $\lambda_1$, $\lambda_2$, and $\lambda_3$ are different wavelengths with the relation $\lambda_1 > \lambda_2 > \lambda_3$. As previously discussed, the depth circle for the longest wavelength $\lambda_1$ has the smallest radius. In this way, one point in real space is acquired by the imaging sensor and a specific wavelength is assigned to it.

### 3. INVERSE CONVERSION ALGORITHM FROM RGB COLOR TO DEPTH

In the AODC camera, the RGB color image is recorded by an image sensor with RGB color filters instead of the HSI sensor. In order to reconstruct the depth information from the RGB color, a special inverse conversion algorithm is demanded. The relation between the wavelength and the RGB color space depends on the system parameters, such as the spectrum of the light source and the response of the image sensor. Thus, the white light source and the image sensor in our system are characterized, and then the matching table for inverse conversion is obtained.
In order to characterize the white light source and the image sensor, the RGB color image of the slanted object is recorded. Figure 4 shows the color-matching function of the image sensor, EOS 650D from Canon. \( R, G, \) and \( B \) mean color indices by the image sensor, and they have some resemblance to the CIE color-matching functions in colorimetry.

\( R, G, \) and \( B \) values are understood as the integration of the product of spectral reflectance of the object, \( S(\lambda) \), spectral power distribution of the illuminant, \( I(\lambda) \), and transmittance of the color filter, \( r, g, \) and \( b \). Therefore, they are represented as

\[
R = \int_{0}^{\infty} S(\lambda)I(\lambda)\tilde{r}(\lambda)\,d\lambda, \tag{5a}
\]

\[
G = \int_{0}^{\infty} S(\lambda)I(\lambda)\tilde{g}(\lambda)\,d\lambda, \tag{5b}
\]

\[
B = \int_{0}^{\infty} S(\lambda)I(\lambda)\tilde{b}(\lambda)\,d\lambda. \tag{5c}
\]

Figure 5 shows the trajectory of the discrete wavelength signal in RGB color space. The discrete wavelength signal is represented as a curve, and it is hard to match one RGB color with a wavelength. For matching, color luminance also needs to be considered since this value changes according to the surface properties of the object, even though the object has the same white color. The effect of the color luminance is deleted by normalizing the measurement of RGB color as follows:

\[
r = R/(R + G + B), \tag{7a}
\]

\[
g = G/(R + G + B), \tag{7b}
\]

\[
b = B/(R + G + B). \tag{7c}
\]

Here, \( r, g, \) and \( b \) are normalized values and they are placed on the slanted plane \( r + g + b = 1 \), as shown in Fig. 6.

In the normalized rgb plane, the color vector of the discrete wavelength signal \( \lambda_c \) is defined by

\[
\mathbf{V}_c = (r_c, g_c, b_c). \tag{8}
\]

Likewise, the measurement vector from the image sensor in the AODC camera is also expressed as

\[
\mathbf{W} = (r_w, g_w, b_w). \tag{9}
\]

In an ideal case, the measurement vector \( \mathbf{W} \) is placed on the trajectory of the color vector \( \mathbf{V}_c \), but practically the error between them always exists. Thus, the estimation of the wavelength \( \tilde{\lambda}_c \) is selected by finding a minimum argument between \( \mathbf{W} \) and \( \mathbf{V}_c \) as follows:

\[
\tilde{\lambda}_c = \arg \min_{\lambda_c} ||\mathbf{W} - \mathbf{V}_c||. \tag{10}
\]

The error mainly results from the nonlinearity of the response of the image sensor depending on the color luminance and weakens the justification of the normalization process. Another limitation originates from the widths of the slits in the projection part and the gating part. In Eq. (5), the spectral power distribution of the illuminant, \( I(\lambda) \), is assumed as a delta function. However, the slit has a width of about 1 mm, and this

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**Fig. 4.** Color-matching function of the image sensor with the white light source.

**Fig. 5.** Trajectory of the discrete wavelength signal \( \lambda_c \) in RGB color space.
width is chosen in consideration of the efficiency of the optical power.

The inverse conversion algorithm has two critical limitations for applications of the AODC camera. First, it is necessary to block environment light. Environment light functions as the bias value, and the measured RGB color is shifted by the addition of the bias value in RGB space. Therefore, the resultant normalized values \((r, g, b)\) become different from the correct ones. Next, the only achromatic-colored object is available for the AODC camera. In the AODC camera, one point in RGB color space corresponds to a specific depth. Therefore, the object that does not reflect some optical spectrum becomes invisible within the corresponding range of the depth.

### 4. EXPERIMENTAL RESULTS

The inverse conversion algorithm is applied to two distinct experiments to show its feasibility. For these experiments, a grating with 600 grooves/mm is used and the bias angle \(\phi_k\) is set 3.153 rad. EOS 650D is used as the image sensor, and it is characterized following the method explained in Section 3.

As the first example, a set of objects with previously known positions are measured and the position errors are evaluated. The objects are nine balls hanging by strings, as shown in Fig. 7. Each position from the reference point of the camera lens is listed in Table 1.

Figure 8 shows an RGB color image and a reconstructed depth map. The nine balls are colored by different colors depending on their depth. The nearest ball with No. 9 is colored with dark red, and the farthest ball with No. 1 is colored with dark violet. In addition, the other balls are colored with various colors, such as yellow, green, sky blue, and violet, according to their depths. Balls with Nos. 3, 4, and 5 have similar colors. However, these balls have different depths from the AODC camera. In addition, the ball with No. 8 shows a red-to-yellow spectrum from the left to the right of the ball. If the color is determined only according to the distance from the AODC camera, the left and right sides of the ball will be colored with the same color symmetrically. However, the red-to-yellow spectrum appears on the ball with No. 8 since the AODC camera colors the object according to the depth circle. Figure 8(b) exhibits the reconstructed image that is shaded according to depth information.

Table 2 shows the estimated wavelength and the inversely converted positions of the nine balls and the estimation errors. When two balls with Nos. 8 and 9 are compared, it can be seen that the ball with No. 8 has a longer distance than the ball with No. 9, even though the wavelength of the former is longer than that of the latter. Similar change of the order happens between the balls with Nos. 3 and 4. These results demonstrate that the AODC camera colors the objects depending on the radius of the depth circle as previously discussed. The errors are distributed from 4.1 to 22.6 mm.

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**Fig. 6.** Trajectory of the discrete wavelength signal \(\lambda_i\) in the normalized \(rgb\) plane.

**Fig. 7.** Experimental setup for measuring the positions of nine balls.

**Table 1.** Positions of the Nine Balls with the Reference Point of the Camera Lens as the Origin

<table>
<thead>
<tr>
<th>Ball No.</th>
<th>(x)</th>
<th>(y)</th>
<th>(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-27.0</td>
<td>67.0</td>
<td>812.0</td>
</tr>
<tr>
<td>2</td>
<td>-112.0</td>
<td>4.0</td>
<td>725.0</td>
</tr>
<tr>
<td>3</td>
<td>13.0</td>
<td>-101.0</td>
<td>705.0</td>
</tr>
<tr>
<td>4</td>
<td>-63.0</td>
<td>-33.0</td>
<td>676.0</td>
</tr>
<tr>
<td>5</td>
<td>-31.0</td>
<td>39.0</td>
<td>661.8</td>
</tr>
<tr>
<td>6</td>
<td>11.0</td>
<td>4.0</td>
<td>613.0</td>
</tr>
<tr>
<td>7</td>
<td>-68.0</td>
<td>71.0</td>
<td>583.5</td>
</tr>
<tr>
<td>8</td>
<td>37.0</td>
<td>-31.0</td>
<td>573.0</td>
</tr>
<tr>
<td>9</td>
<td>50.0</td>
<td>77.5</td>
<td>520.0</td>
</tr>
</tbody>
</table>

**Fig. 8.** (a) RGB color image by the AODC camera, and (b) the depth map inversely converted from the RGB color image.
The results in Table 2 show a tendency that the error in the short wavelength is relatively larger than that in the long wavelength. This phenomenon is understood for several reasons. One reason is that the trajectory of the color vector $V_c$ is bent. The root-mean-square (RMS) distance of the color vector at a given wavelength from the overall trajectory of the color vector is defined by

$$d(\lambda_c) = \sqrt{\frac{1}{m-1} \sum_{k} \|V_c - V_k\|^2}. $$  \hspace{1cm} (11)

This RMS distance has relatively small values from 480 to 600 nm, as shown in Fig. 9. The RMS distance is related to the ambiguity of finding a minimum argument between $W$ and $V_c$ in Eq. (10). Another reason is that the short wavelength corresponds to deep depth. Therefore, it is more sensitive to the errors in the angles as the system parameters such as the angles of the ray projected on the object $\theta_L$ and the angle of the ray received by the gate $\theta_C$.

As the second example, the scale object is measured and reconstructed. Figure 10 shows the experimental setup, where the object with the valley and peak is made of paper mache clay. We recorded images of the portion of the object while translating the AODC camera. Figures 11(a)–11(l) exhibit the RGB color image directly recorded by the AODC camera at the different positions where the intervals between adjacent images are 130 mm vertically and 140 mm horizontally. The recorded images are colored as if the contour lines exist. The mountain-shaped peak looks reddish, and the yellow and greenish parts appear below the peak. The lowest portion at the valley is colored by blue. However, the image stitching is not simple since the boundaries of the raw images in Figs. 11(a)–11(l) do not match.

<table>
<thead>
<tr>
<th>Ball No.</th>
<th>$\lambda_c$ (nm)</th>
<th>$x$</th>
<th>$y$</th>
<th>$z$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>452.9</td>
<td>-23.5</td>
<td>67.8</td>
<td>814.0</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>477.7</td>
<td>-124.2</td>
<td>2.0</td>
<td>744.0</td>
<td>22.6</td>
</tr>
<tr>
<td>3</td>
<td>513.1</td>
<td>18.6</td>
<td>-117.2</td>
<td>707.0</td>
<td>17.2</td>
</tr>
<tr>
<td>4</td>
<td>517.1</td>
<td>-64.7</td>
<td>-34.2</td>
<td>692.5</td>
<td>16.6</td>
</tr>
<tr>
<td>5</td>
<td>511.4</td>
<td>-35.9</td>
<td>38.6</td>
<td>675.7</td>
<td>14.7</td>
</tr>
<tr>
<td>6</td>
<td>564.9</td>
<td>9.8</td>
<td>1.6</td>
<td>598.9</td>
<td>14.3</td>
</tr>
<tr>
<td>7</td>
<td>582.9</td>
<td>-76.8</td>
<td>62.6</td>
<td>587.7</td>
<td>12.8</td>
</tr>
<tr>
<td>8</td>
<td>621.8</td>
<td>37.2</td>
<td>-35.0</td>
<td>575.0</td>
<td>4.4</td>
</tr>
<tr>
<td>9</td>
<td>617.8</td>
<td>52.8</td>
<td>70.9</td>
<td>521.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Fig. 9. RMS distance of the color vector at a given wavelength from the overall trajectory of the color vector.

Fig. 10. Experimental setup for measuring the morphology of large-scale objects by stitching several RGB color images.

Fig. 11. (a)–(l) RGB color image directly recorded by the AODC camera at the different positions, and (m) the reconstructed morphology by stitching twelve RGB color images.
meet each other. It results from the curvature of the depth circle.

Figure 11(m) shows the stitched morphology of the object. With Eqs. (4) and (10), the depth of the object is computed, but the seam between adjacent parts still appears vaguely due to vignetting of the relay lens in front of the image sensor. This relay lens transforms the image plane onto the image sensor. As mentioned in Section 3, the inverse conversion is based on the linearity of the response of the image sensor and the vignetting problem makes a difference in the color luminance. Therefore, it may worsen our estimation due to the nonlinearity of the response of the image sensor.

In order to evaluate the reconstructed result, the target object is measured by two different methods. One is an IR projection 3D scanner, Sense 3D Scanner from 3D Systems. Its scanning range is between 7 and 72 inches and has a depth resolution of about 1 mm at a distance of 0.5 m. The other is a line laser 3D scanner, which is established as shown in Fig. 12. For extracting the depth map of the object, a single line pattern made by the line pattern generator is projected onto the object. The distortion pattern is measured by using a telecentric lens and a charge-coupled device (CCD) camera in a different position.

Figure 13 shows a comparison of the experimental results by the AODC camera, the IR projection 3D scanner, and the line laser 3D scanner along the cross section. This cross section is depicted from A to A’ in Fig. 13(a). The IR projection 3D scanner and the line laser 3D scanner provide very similar results. The small difference is understood due to the algorithm of the IR projection 3D scanner that makes the surface smooth. The measurement error in the AODC increases accordingly as the height of the object decreases. The top region is colored by red and the region with lower height is colored by green in Figs. 11(a)–11(l). This phenomenon has good agreement with the tendency of the error as discussed previously in Table 2.

5. CONCLUSION

The AODC camera represents depth information of an object as RGB color corresponding to a specific wavelength. Since RGB color space is 3D, it is hard to inversely convert one point in RGB color space into a wavelength. In this paper, we suggest an inverse conversion algorithm from RGB color to depth information for the AODC camera. Our inverse conversion algorithm is based on the condition that the depth information is not fully 3D but a curved 2D surface. Therefore, it is rational that the measured color vector in RGB color space is projected on the normalized rgb plane. The grating in the AODC camera disperses the light source and the points on the depth circle are assigned by the same wavelength. The relation between the wavelength and the RGB color space depends on the spectrum of the light source and the response of the image sensor. Thus, the light source and the image sensor in our system are characterized, and then the matching table for inverse conversion is found. The feasibility is confirmed by experiments, and the measurement errors mainly result from the nonlinearity of the response of the image sensor and the widths of the slits in the projection part and the gating part. In the future, we plan to replace the moving parts with optoelectronic components.

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