Optical Watermarking Technique Robust to Geometrical Distortion in Image

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Abstract -- This paper presents an optical watermarking technique that is robust against geometrical distortion in images by using spatially modulated illumination. It can protect "analog" objects like pictures painted by artists from having photographs taken of them illegally in museums. Illegally captured images in practical situations may contain various distortions, and embedded watermarks may be incorrectly detected. Geometrical distortion caused by the shooting angle that the objects are captured at is a particularly major problem. We carried out experiments to evaluate the robustness of watermarking images that were geometrically distorted, in which distortions were intentionally created by moving the position of the projector and the digital camera from right in front of the object. The accuracy of the extracted watermarking data was almost 100%, even if the shooting angle was inclined by about 20 degrees between the projector and digital camera, in both cases when a Discrete Cosine Transform (DCT) and a Walsh-Hadamard Transform (WHT) were used as the methods of embedding watermarks. We introduced rectangular mesh fitting and a technique of "bi-linear interpolation" based on the four nearest points to correct the distortions.

Keywords—Digital watermarking, Illuminated digital watermarking, Spatially modulated illumination, Illegal photography protection, Geometrical distortion

I. INTRODUCTION

Techniques of digital watermarking have recently been widely recognized as methods of protecting the copyright of digital-image content that is increasingly being distributed throughout the Internet [1]-[3]. In case of printed images, digital watermarking is embedded in the digital data before it is printed [4]-[5]. However, this method cannot prevent pictures of valuable paintings that are exhibited at museums and galleries from illegally being captured with digital cameras.

We previously proposed a novel technology that could prevent the illegal use of images of objects that did not have watermarking [6]. This technique used illumination that contained invisible watermarking. As the illumination for the object contained watermarking, images of the object taken with a camera also contained watermarking and this could be extracted by image processing. We used a Walsh-Hadamard Transform (WHT) as well as a Discrete Cosine Transform (DCT) as methods of embedding the watermarking [7]. However, when the practical case of images being illegally capturing by digital cameras in art museums is considered, most photographed images may contain various distortions such as defocusing, blurring, and geometrical distortion. Geometrical distortion due to the angle images are shot with cameras is a particularly major problem that affects the accuracy with which the data on embedded watermarking images are read out. How these geometrical distortions affect accuracy should be evaluated to enable the practical use of our technology. This paper describes experiments done on a

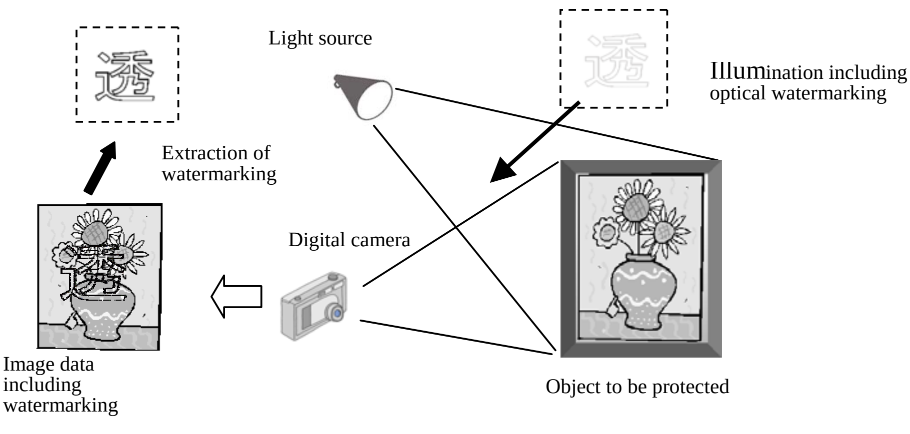

Fig. 1. Basic concept underlying proposed technology

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method of correcting geometrical distortions, and presents results that demonstrate the feasibility of our optical watermarking technology.

II. PROPOSED DIGITAL WATERMARKING INPARTED BY ILLUMINATION

Fig.1 outlines the basic concept underlying the optical watermarking technology we have proposed. The light source contains the watermarking information and illuminates an object. A projector can be used as the light source that provides a distribution of 2D-illumination. The brightness of the object's surface is proportional to the product of the reflectance of the surface and the illumination by the light source. Therefore, this technology can be applied to "analog" objects such as pictures painted by artists that are difficult to electronically embed with watermarking. Moreover, the technology also offers the possibility of being applied not only to flat or 2D objects but also 3D objects and moving objects.

Fig. 2 illustrates the procedure for watermarking using orthogonal transforms. The watermarking area is divided into units of 16×16 or 8×8 pixel blocks, and each block has a DC component that gives an average brightness for the entire watermarking area, i.e., brightness of illumination. Every block also has the highest frequency component (HC) in both the x - and y -directions to express the 1-bit binary information for watermarking. We used the phase of HC to express binary data i.e., "0" or "1". Two orthogonal transforms were used to produce the watermarking images. The first was a 2D inverse DCT (i-DCT), which is mathematically expressed by Eq. (1).

$$f_{i,j}(x,y) = \sum_{u}^{N-1}\sum_{v}^{N-1} C(u)C(v)F_{i,j}(u,v)\cos\{\frac{(2x+1)u\pi}{2N}\}\cos\{\frac{(2y+1)v\pi}{2N}\} \tag{1}$$

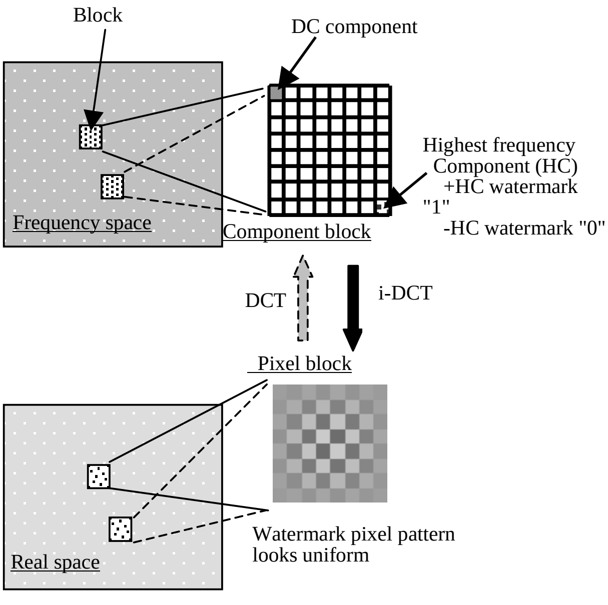

Fig. 2. Producing watermarks

where $f_{i,j}(x,y)$ are the watermarking image data for pixel (x,y) of block (i,j) in real space, $F_{i,j}(u,v)$ are the data for component (u,v) of block (i,j) in frequency space, and N is the number of pixels in the block in the x - and y -directions. Here, $C(u)$ and $C(v)$ are given as

$$C(u) = \begin{cases} 1 & (u=0) \\ \sqrt{2} & (u \neq 0) \end{cases} \quad , \qquad C(v) = \begin{cases} 1 & (v=0) \\ \sqrt{2} & (v \neq 0) \end{cases}$$

The second was a 2D inverse WHT (i-WHT), which is expressed by Eq. (2).

$$f_{i,j}(x,y) = \frac{1}{N}\sum_{u}^{N-1}\sum_{v}^{N-1} F_{i,j}(u,v)wh(x,u)wh(v,y) \tag{2}$$

where $wh(i,j)$ denotes a component of the Walsh-Hadamard matrix in Table 1.

Table 1. Walsh-Hadamard Matrix

(a) 8×8 Matrix

1	1	1	1	1	1	1	1
1	1	1	1	−1	−1	−1	−1
1	1	−1	−1	−1	−1	1	1
1	1	−1	−1	1	1	−1	−1
1	−1	−1	1	1	−1	−1	1
1	−1	−1	1	−1	1	1	−1
1	−1	1	−1	−1	1	−1	1
1	−1	1	−1	1	−1	1	−1

(b) 16×16 Matrix

1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	−1	−1	−1	−1	−1	−1	−1	−1
1	1	1	1	−1	−1	−1	−1	−1	−1	−1	−1	1	1	1	1
1	1	1	1	−1	−1	−1	−1	1	1	1	1	−1	−1	−1	−1
1	1	−1	−1	−1	−1	1	1	1	1	−1	−1	−1	−1	1	1
1	1	−1	−1	−1	−1	1	1	−1	−1	1	1	1	1	−1	−1
1	1	−1	−1	1	1	−1	−1	−1	−1	1	1	−1	−1	1	1
1	1	−1	−1	1	1	−1	−1	1	1	−1	−1	1	1	−1	−1
1	−1	−1	1	1	−1	−1	1	1	−1	−1	1	1	−1	−1	1
1	−1	−1	1	1	−1	−1	1	−1	1	1	−1	−1	1	1	−1
1	−1	−1	1	−1	1	1	−1	−1	1	1	−1	1	−1	−1	1
1	−1	−1	1	−1	1	1	−1	1	−1	−1	1	−1	1	1	−1
1	−1	1	−1	−1	1	−1	1	1	−1	1	−1	−1	1	−1	1
1	−1	1	−1	−1	1	−1	1	−1	1	−1	1	1	−1	1	−1
1	−1	1	−1	1	−1	1	−1	−1	1	−1	1	−1	1	−1	1
1	−1	1	−1	1	−1	1	−1	1	−1	1	−1	1	−1	1	−1

In both methods, $F_{i,j}(u,v)$ is given as

$$F_{i,j}(0,0) = \text{DC} \tag{3}$$

$$F_{i,j}(N-1,N-1) = \begin{cases} \text{HC, if binary data to be embedded in block } (i,j) \text{ are "1"} \\ \text{-HC, if binary data to be embedded in block } (i,j) \text{ are "0"} \end{cases} \tag{4}$$

$$F_{i,j}(u,v) = 0 \quad (\text{ for } \; u,v \neq 0, \; \text{N-1}) \tag{5}$$

Eqs. (3)-(5) indicate that the produced image only has the DC component and HC , and the other components are set to "0". Therefore, the embedded watermarking image projected onto the object using a projector could barely be seen by the human-visual system but it could easily be read out from the object image. Because the frequency components of the object image itself were lower than the HC, the embedded information for watermarking was easily separated from the object image.

III. EXPERIMENTS AND RESULTS

Watermarking images that consisted of 16 × 16 blocks were produced in the experiments. Each block had 8 × 8 pixels, i.e., the watermarking images had 128 × 128 pixels. A Digital Light Processing (DLP) projector was used as a light source that had a resolution of 800 × 600 pixels. The watermarking images were projected onto pictures as the objects, which were printed A4 images of the standard image data. The values for DC and HC were changed as they were the experimental parameters.

We selected several positions for the camera to take the photographs and for the projector to irradiate the watermarking images that were inclined from the normal direction from about the center point of the projector image irradiated onto the object (printed image) plane. The images of pictures taken under such conditions were distorted from a rectangular shape with accurately irradiated regions of optical watermarking. Fig. 3 shows the layout for the projector, the digital camera, and the object in the experiments. Note that the optical axis of the projector is pointing upward from the horizontal line. The projected area is also positioned upward on the object plane from the horizontal line, although the shape of the image irradiated on the object plane is automatically corrected to a precise rectangle. Table 2 lists detailed descriptions on the positions of the projector and digital camera. The optical axis for the camera or the projector is the line from the former or latter to the center point of the projected area. Fig.4 has an image that was captured under the "P3" condition in Table 2.

Distorted image data taken with the digital camera were corrected as will be explained later. Then, a corrected rectangular domain was clipped out as an area that was brighter than its neighbors due to illumination. The resolution of the clipped area was about 800 × 800 pixels using a digital camera with a resolution of 4288 × 2848 pixels. It was then transformed to just 256 × 256 pixels, and divided into 16 × 16 blocks each of which had 16 × 16 pixels. We carried out DCT on all blocks using Eq. (6).

$$F_{i,j}(u,v) = \frac{C(u)C(v)}{M \times M} \sum_{x}^{M-1} \sum_{y}^{M-1} f_{i,j}(x,y) \cos\{\frac{(2x+1)u\pi}{2M}\} \cos\{\frac{(2y+1)v\pi}{2M}\} \tag{6}$$

We also utilized Eq. (7) for WHT, using the values in Table 1(b) as the components of matrix $wh(i,j)$.

$$F_{i,j}(u,v) = \frac{1}{M} \sum_{x}^{M-1} \sum_{y}^{M-1} f_{i,j}(x,y) wh(u,x) wh(y,v) \tag{7}$$

where M is the number of pixels in the u and v directions in frequency space, which was 16 in the experiments.

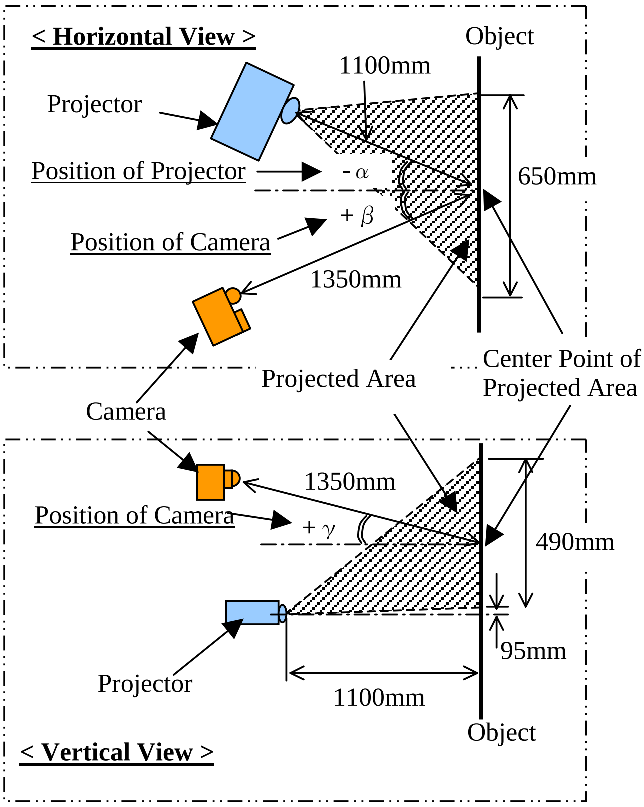

Fig.3. Layout of equipment in experiments

Table 2. Positions of projector and digital camera
(*: units=degrees)

Position	Projector		Camera		Angle between optical axes of projector and
	Horizontal *	Vertical *	Horizontal *	Vertical *	
P1	10	0	0	0	10
P2	10	0	13	8	22
P3	10	0	13	-5	21

The accuracy with which the embedded data were read out was evaluated by checking the sign of the $F_{i,j}(7,7)$ components for all blocks. Two methods of embedding data were used. The "1-block method" involved embedding 1-bit data into one block, and embedding 256 1-bit binary data into 16 × 16 blocks. The "majority method" involved embedding the same 1-bit data into three blocks sufficiently separated from one another, and it determined the readout data using a majority decision. The distance between the blocks was set to five in the experiments and 75 1-bit binary data were embedded into 16 × 16 blocks.

First, we carried out an experiment to restore these distortions using a method of correction with which the irradiated region of optical watermarking was considered to be quadrilateral that was created with four corner points in the region; we corrected this as the entire area might become a precise square. Transformation from an undistorted coordinate system (x, y) to a geometrically distorted system (x', y') is generally expressed with the following equations.

$$x' = h_1(x, y), \quad y' = h_2(x, y) \tag{8}$$

If the distortion is perspective, the transformation is expressed with the following linear equations.

$$x' = ax + by + d, \quad y' = dx + ey + f \tag{9}$$

The shape of the image containing the generated watermarks is a precise rectangle. However, if these were distorted in perspective, they become general quadrangles. When the coordinates of all corner points of a quadrangle are given, the coefficients of the above-mentioned linear expression can be determined from three of these and the corresponding coordinates of the original undistorted rectangle. The value of pixels in the distorted quadrangle can be transformed to the value of pixels in the undistorted rectangle by using these equations. However, because the coordinates of the transformed pixels do not generally become integers, an interpolation technique is utilized to determine the density value of the nearest pixel. Linear transformation using the four nearest neighboring pixels was used in these experiments, which is so called "bi-linear interpolation" [9].

The size of the corrected rectangular area was about 800 × 800 pixels as previously mentioned. We evaluated the accuracy with which the embedded data were read out in both cases of DCT and WHT using the corrected image data. The results obtained by using the first method were, however, insufficient as we expected. The rate at which embedded data were correctly read out was under 50% under all conditions of HC values, positions, and methods of embedding the data. We investigated the details on the corrected image data as to whether all 8 × 8 pixel blocks were equally divided in all regions of the corrected area. We consequently found these were not linearly distorted in any region of the clipped out area.

Fig.4. Distorted image with watermarking: (WHT, DC=150, HC=15)

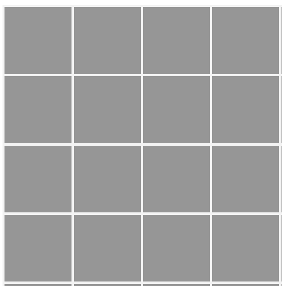

Fig.5 (a). Grid pattern image

Fig.5 (b). Distorted image with grid

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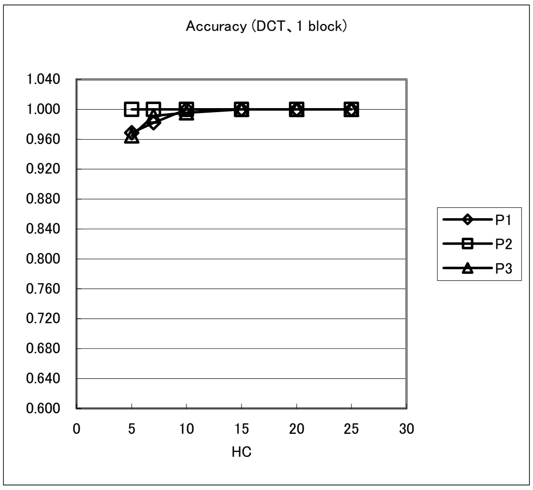

Fig. 6. (a) Accuracy with which data were read out with method using the grid pattern: (DCT , 1-block evaluation)

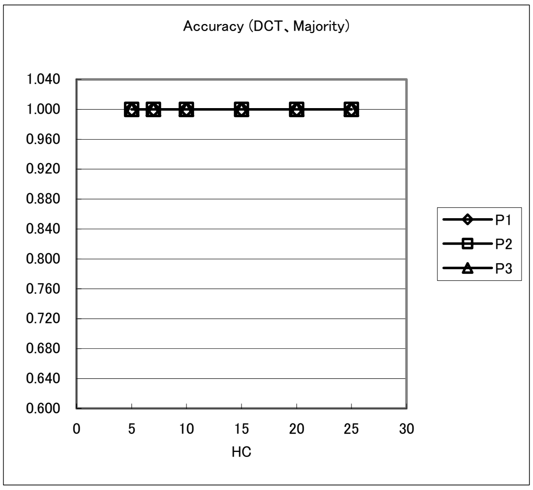

Fig. 6. (b) Accuracy with which data were read out with method using the grid pattern: (DCT, Majority of 3-block evaluation)

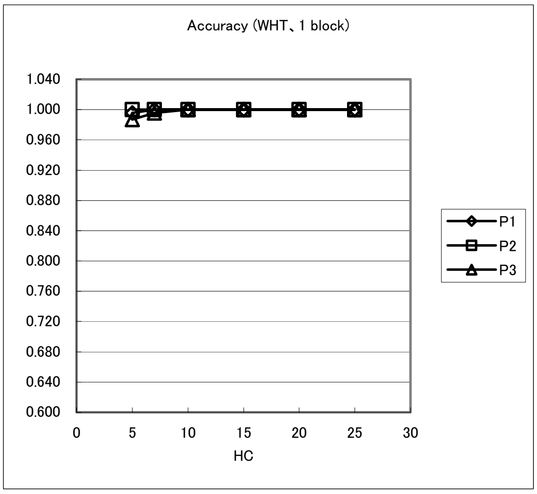

Fig. 6. (c) Accuracy with which data were read out with method using the grid pattern: (WHT , 1-block evaluation)

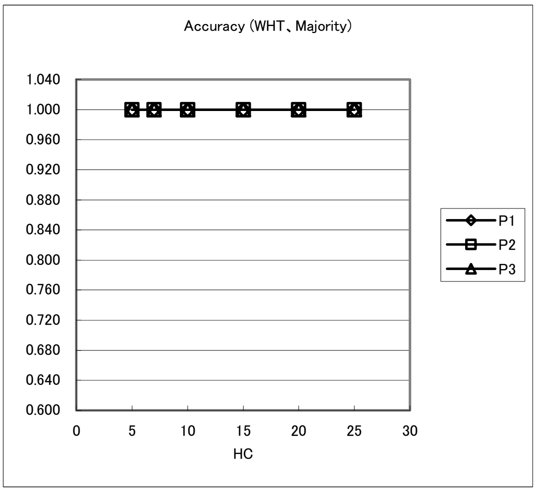

Fig. 6. (d) Accuracy with which data were read out with method using the grid pattern: (WHT , Majority of 3-block evaluation)

In the second method we carried out, the image of the grid pattern that divided the region of optical watermarking equally into 4 × 4 was first irradiated onto the object image (Fig. 5 (a)) and captured with a digital camera. The coordinates of the corner points for the segmented areas were manually measured on the captured image data. Then, the image data irradiated with optical watermarking were captured, and they were corrected by using the coordinates of the corner points for all segmented areas as they became exact squares. The method used to correct distortion in all segmented areas was the same as the first approach. Fig. 5 (b) has the captured image irradiated with a grid pattern, which was also taken from the "P3" position listed in Table 2.

The results obtained from evaluating the rate at which embedded watermarking information was detected using the second method are in Fig. 6 (a)-(d). Occasionally, the accuracy of detection did not reach 100% for HC=10 or less under the P1 and P3 conditions with the 1-block method while it was 100% under P2 conditions when both DCT and WHT were used. However, the accuracy of detection was 100% under all conditions with the majority method.

IV. DISCUSSION

We assumed that distortion occurred equally in all areas in the image irradiated with optical watermarking in the first method of correcting geometrical distortions, so that the pixels in the original rectangle area were transformed to be uniformly distributed in a general quadrangle. However, the results were different from what we expected. The reasons for such non-linearity in geometrical distortion were not necessarily clear. However, the characteristics of the projector used in the experiments possibly caused this phenomenon.

The results obtained from evaluation roughly agreed with those from past experiments using the second method of correction. These results indicated geometrical distortions could be precisely corrected if the rectangular domains could be cut out comparatively well in small block units by using the grid for the irradiated region of the watermarking image.

V. CONCLUSION

We proposed a robust technique of optical watermarking using a method of rectangular mesh fitting and a technique of "bi-linear interpolation" based on the four nearest points as a method of correcting the geometrical distortion. We considered that, in practice, usually geometrical distortions were produced in illegally captured photographs taken with digital cameras in museums and they might affect the detection rate of optical watermarks. We evaluated how these geometrical distortions affected the accuracy with which data in embedded watermarking images was read out. To do this, we artificially created distortions when an image of embedded optical watermarking was captured and evaluated the accuracy with which embedded data were detected after geometrical distortions were corrected. We found that the embedded data were read out with 100% accuracy with DCT and WHT for embedded watermarking after distortions had been corrected. We used a method of correcting distortions where we projected a grid pattern image to indicate the correct pixel block, prior to images of embedded watermarking being captured. However, if a marker was also embedded in the optical watermarking images, it could easily be extracted with image processing. For example, if a grid pattern image and watermarking image had different colors and were embedded simultaneously, they could easily be separated from each other. Therefore, geometrical distortions in optical watermarking images caused in such practical situations could be restored, and the embedded data could also be correctly extracted. This revealed the feasibility of the technique of optical watermarking to protect objects from being illegally captured, which has been difficult to accomplish with conventional watermarking technology.

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