PROTECTION OF 3D OBJECTS AGAINST ILLEGAL PHOTOGRAPHY USING OPTICAL WATERMARKING TECHNIQUE WITH SPATIALLY MODULATED ILLUMINATION

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Abstract: We present a new technique that protects the copyrights or portrait rights of 3D objects such as sculptures, merchandise, and even human bodies, with optical watermarking, which is produced by spatially modulated illumination. Although the previous study revealed that the optical watermarking technique could prevent objects from being illegally photographed without protection, the technique could only be applied to 2D objects. The largest problem to be solved in extending this technique to the case of 3D objects is to compensate for geometrical distortion. We solved this problem by introducing rectangular mesh fitting and a technique of "bi-linear interpolation" based on the four nearest points. We conducted experiments in which we projected optical watermarking onto the surface of a globe and a model of the human face, and evaluated the accuracy of extracted data. The results were almost 100% in both cases when a Discrete Cosine Transform (DCT) and a Walsh-Hadamard Transform (WHT) were used as methods of embedding watermarks.

1 INTRODUCTION

Techniques of digital watermarking have been widely recognized in recent years as methods of protecting the copyrights of digital image content. For example, digital watermarking is embedded in digital data before it is printed to protect paper images. This is the same as for other types of digital media. However, this method cannot prevent photographs of valuable paintings at museums and galleries from being illegally taken with digital cameras.

We have proposed a novel technology that can prevent the illegal use of images of objects that do not have watermarking, using illumination with invisible watermarking. We carried out experiments and revealed that watermarking data were read out with almost 100% accuracy. In this paper we propose the optical watermarking technology applying to real 3D objects like sculptures in museums, merchandise in stores, or even human bodies on stages.

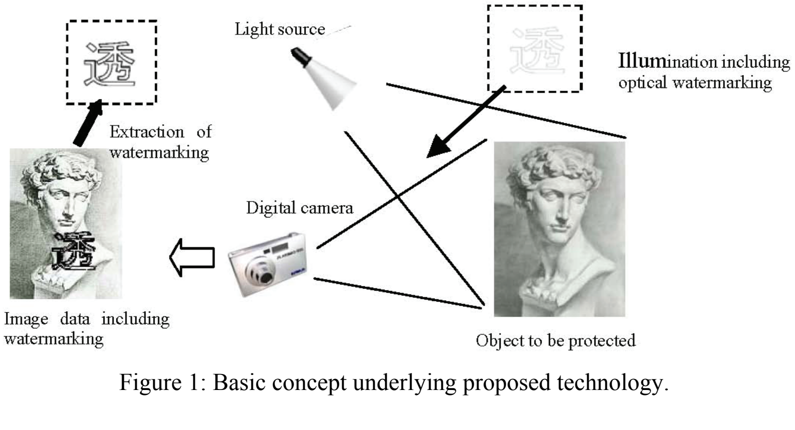

Figure 1: Basic concept underlying proposed technology.

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2 WATERMARKING TECHNIQUE APPLYING TO BASIC 2D OBJECTS

Fig. 1 outlines the basic concept underlying the optical watermarking technology. A projector is possibly used as the light source that contains the watermarking information and illuminates an object. 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.

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., the 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. The phase of HC was used to express binary data i.e., "0" or "1". Other components than DC or HC were set to "0". DCT and WHT were used as orthogonal transforms to produce the watermarking images. The equations of i-DCT and i-WHT are expressed with Eq. (1) and Eq. (2) respectively.

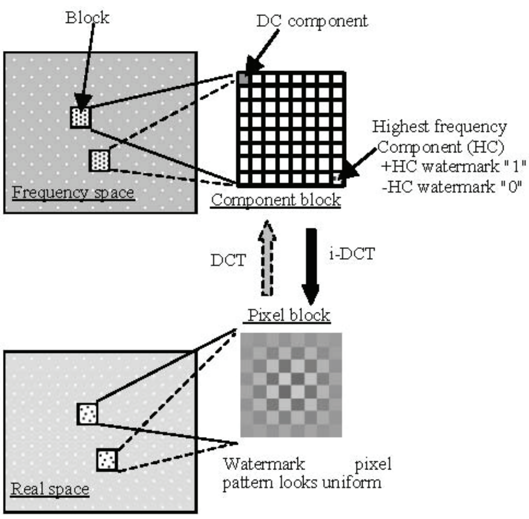


Figure 2: Producing watermarks.

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

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

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

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

and $wh(i,j)$ 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

3 APPLYING TO 3D OBJECT

First, the grid pattern image that divides the region of the optical watermarking equally into 8 × 8 is irradiated onto the object image and captured with a digital camera to apply optical watermarking technique to 3D objects. The coordinates of the corner points of the segmented areas are measured respectively on the captured image data. Then, the image data irradiated with optical watermarking are captured, and these are corrected by using the coordinates of the corner points of the segmented area as each segmented region may become a precise square.

The transformation from an undistorted coordinate system (x, y) to a geometrically distorted system (x', y') is generally expressed by following equations.

$$x' = h_1(x, y), \; y' = h_2(x, y) \tag{3}$$

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

$$x' = ax + by + c, \; y' = dx + ey + f \tag{4}$$

Using these equations the value of pixels in the distorted quadrangle can be transformed to the value of pixels in the undistorted rectangle. However, because the coordinates of 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 the experiments, which is so called "bi-linear interpolation".

4 EXPERIMENTS

Watermarking images had 128 × 128 pixels that consisted of 16 × 16 blocks of 8 × 8 pixels in the experiments. A Digital Light Processing (DLP) projector that had a resolution of 800 × 600 pixels was used as a light source. A white hemisphere, a globe, and a model of a human face were used as real 3D objects. Fig. 3. (a) shows the image of a globe irradiated with the grid pattern, and Fig. 3. (b) and (c) have the photographs of the human-face model onto which the watermarking or grid pattern was projected.

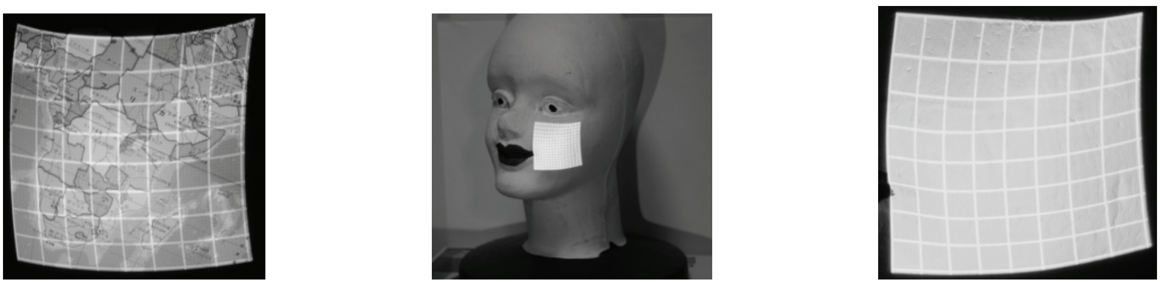
Using the measured coordinates of the grid points, each 8 × 8 divided segments were identified and were corrected to a precise rectangle as described in the previous section. The restored rectangular area had about 650 × 650 pixels using a digital camera with a resolution of 4288 × 2848 pixels. It was transformed to 256 × 256 pixels and divided into 16 × 16 blocks. We carried out DCT on all blocks using Eq. (5).

$$F_{i,j}(u,v) = \frac{C(u)C(v)}{M \times M} \sum_{x}^{M-1} \sum_{y}^{M-1} f_{i,j}(x,y) \bullet \cos\{\frac{(2x+1)u\pi}{2M}\} \cos\{\frac{(2y+1)v\pi}{2M}\} \tag{5}$$

We also utilized Eq. (6) for WHT, using the values in Table 1(b) as the components of matrix $wh(i, j)$ and $M = 16$.

$$F_{i,j}(u,v) = \frac{1}{M} \sum_{x}^{M-1} \sum_{y}^{M-1} f_{i,j}(x,y) wh(u,x) wh(y,v) \tag{6}$$

The accuracy of reading out the embedded data 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 the readout data were determined by the majority decision. The distance between the blocks was set to five and 75 1-bit binary data were embedded in 16 × 16 blocks in the experiments.



(a) Grid pattern on a globe (b) Human-face model (c) Magnified image of the grid pattern on a human-face model

Figure 3: Photographs of a globe and a human-face model on which image was projected.

Table 2: Experimental results: Accuracy with which embedded data were read out.

		1-block method						Majority method					
	HC →	5	7	10	15	20	25	5	7	10	15	20	25
DCT	white-ball	1	1	1	1	1	1	1	1	1	1	1	1
	globe-1	0.964	0.964	0.964	0.966	0.982	0.996	1	1	0.987	1	1	1
	globe-2	0.996	0.996	1	1	1	1	1	1	1	1	1	1
	face-1	1	0.996	0.991	1	1	1	1	1	1	1	1	1
	face-2	1	1	1	1	1	1	1	1	1	1	1	1
WHT	white-ball	1	1	1	1	1	1	1	1	1	1	1	1
	globe-1	0.969	0.987	0.991	0.982	0.996	1	1	1	1	1	1	1
	globe-2	1	1	1	1	1	1	1	1	1	1	1	1
	face-1	1	1	1	1	1	1	1	1	1	1	1	1
	face-2	1	1	1	1	1	1	1	1	1	1	1	1

5 RESULTS AND DISCUSSION

Table 2 lists the overall results of experiments. In the table "white-ball" means that a white hemisphere was used as 3D object. In the same way, "globe-1" means European-African hemisphere of a globe was used, "globe-2" means Pacific-Ocean hemisphere of a globe was used, "face-1" means cheek of a human-face model was used and "face-2" means forehead of a human-face model was used. The results of evaluating accuracy for the white hemisphere had 100% under all conditions with DCT and WHT. However, 100% accuracy was not achieved in evaluating accuracy with the globe, especially in the European-African hemisphere, where the 1-bit block method was used with DCT and WHT. The decision by using the majority method achieved an accuracy of 100% excluding the HC=10 of DCT. The European-African hemisphere has numerous black lines and characters and these could disturb the accuracy of reading out embedded data.

An accuracy of 100% for the evaluation of the human-face model was obtained under all conditions in the decision by the majority method. The 1- block method achieved an accuracy of 100% excluding part of the DCT. The surface of the human-face model was painted white in this experiment, and the reflectivity of the surface may have been proportional to the brightness of the irradiated optical watermarking.

6 CONCLUSIONS

We proposed the application of optical watermarking to 3D objects, which can prevent real objects like sculptures in museums from being illegally photographed. We used methods of correcting distortions in captured images caused by projecting optical watermarking image onto the curved surface of objects. We found that the embedded data were read out with almost 100% accuracy when DCT and WHT were used for embedding watermarking, after distortions in the captured images had been corrected. In this paper we used a projected grid pattern to indicate the correct pixel block, prior to the images for embedding watermarking being captured. However, if the marker that appropriately identifies pixel blocks is simultaneously embedded into optical watermarking images, it can easily be extracted with image processing. Therefore, we demonstrated the feasibility of using optical watermarking technique to protect real 3D objects from being illegally captured which has been difficult to accomplish with conventional watermarking technology.

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