Practical Evaluation of Illumination Watermarking Technique Using Orthogonal Transforms

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(Invited Paper)

***Abstract*—We have proposed an "Illumination Watermarking" technology with which the images of objects without copyright protection can contain invisible digital watermarking. This technology uses spatially modulated illumination possibly using an orthogonal transform, such as discrete cosine transform (DCT), as the method of embedding watermarks, and it can be applied to objects that do not have electronically embedded watermarking such as pictures painted by artists. We conducted a new series of experiments where one-bit binary data were embedded in one block that consisted of 8×8 pixels using the phase of the highest frequency component generated by a Walsh–Hadamard transform (WHT) as well as DCT. The experimental results revealed that embedded data could be read out with almost 100% accuracy in both cases, where the embedded watermarked image could hardly be observed. We also found that the influence of JPEG compression, which is commonly used in digital cameras, was very small.**

***Index Terms*—Digital watermarking, discrete cosine transform (DCT), illegal photography protection, illuminated digital watermarking, spatially modulated illumination.**

I. Introduction

THE rapid growth of Internet technology has increased the circulation of digital content such as that in image data, which can easily be created in desktop environments with personal computers and peripheral image devices such as image scanners or digital cameras. Protecting the copyright of image information in such environments has therefore become a pressing issue. Techniques of digital watermarking have recently been widely used to protect the copyright of digital-image content [1]–[9]. Also, digital watermarking has been embedded in the digital data before images have been printed [10]–[12]. This has been done to prevent images photographed with digital cameras or copied with scanners from being illegally used. However, this method cannot protect non-digital images, such as pictures that are displayed at museums, which have been painted by artists, from being illegally captured with digital cameras.

We previously proposed a new technology that could prevent images of objects that did not have watermarking from being illegally used [13]. This technique utilized illumination that invisibly contained the watermarking generated by a Discrete Cosine Transform (DCT). When the illumination containing watermarking was beamed onto an object, any image of the object taken with a digital camera also contained watermarking and this could be extracted by image processing. We used a Walsh-Hadamard transform (WHT) as well as DCT as techniques of embedding the watermarking [14]. This paper describes further experiments and presents results that demonstrate the practical feasibility of the technology we have proposed.

II. Proposed Technique of Illumination Watermarking

Fig. 1 outlines the basic concept underlying the technology of digital watermarking we propose, where an object is illuminated by light that contains invisible information for watermarking. As the illumination includes watermarking data, any photographed image of the object illumined with this lighting will also include watermarking. By digitizing this photographed image, watermarking information can be extracted in the same way as with the conventional watermarking technique. The light source provides a distribution of 2D-illumination similar to that beamed with a projector, and the watermarking data are expressed in the form of this 2D-illumination distribution. However, the spatial modulation in illumination has to be imperceptible to the human-visual system. The brightness distribution given by this light source then looks uniform to the observer over the object, the same as if it were lit by conventional illumination. The brightness of the object's surface is proportional to the product of the reflectance of the object's surface and illumination by incident light.

The main attribute of our technology is that the watermarking can be added by light. Therefore, it solves problems in that it can be applied to objects that cannot be electronically embedded with conventional watermarking, such as paintings created by renowned artists. Moreover, it offers the possibility of being applied to 3D objects, such as sculptures, merchandise, and even the human body, as well as its application to 2D objects.

III. Details on Producing Watermarks

Fig. 2 outlines the procedure for watermarking where the area used consists of numerous blocks and each is 16×16 or 8×8 pixels. The average brightness of all blocks is expressed as a DC component in frequency space, which gives an average brightness for the entire area for watermarking, i.e., the brightness of illumination. Also, every block in frequency space has the

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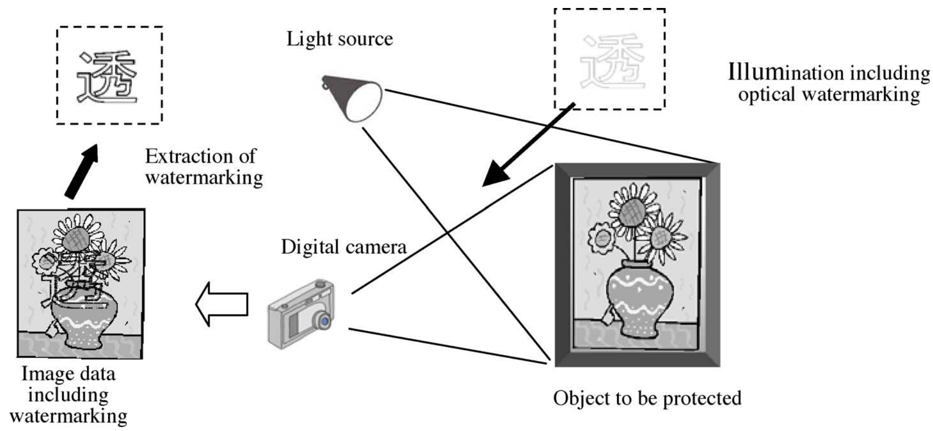


Fig. 1. Basic concept underlying proposed technology.

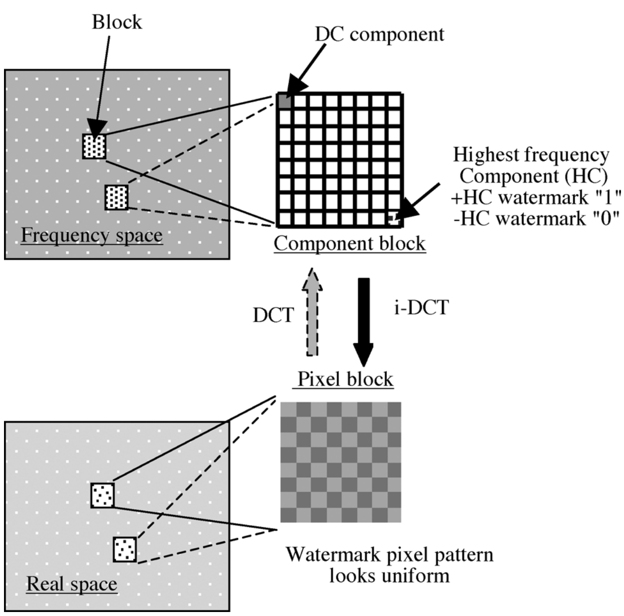


Fig. 2. Producing watermarks.

highest frequency component (HC) in both the x- and y-directions, which express the 1-bit binary information used for watermarking. The phase of HC is used to express binary data, i.e., "0" or "1". If the sign of HC in a block is positive, this is assumed to be expressed as "1", and if the phase is opposite to this (i.e., minus), this is assumed to be expressed as "0".

We used two methods involving orthogonal transforms to generate the watermarking image. The first was 2D inverse DCT (i-DCT), which is expressed by

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

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

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

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

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

where $\mathrm{wh}(i,j)$ stands for a component of the Walsh–Hadamard matrix in Table I.

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

$$F_{i,j}(0,0) = \mathrm{DC} \quad (3)$$

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

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

Equations (3)–(5) indicate that the formed image only has a DC component (the brightness of illumination) and one that is HC, and the other components are set to "0". Therefore, when the produced image was beamed onto the object with a projector, the embedded watermarking image could scarcely be seen by the human-visual system and it could also easily be read out from the object image. Because the frequency components of the object image itself were lower than the HC component, the embedded information for watermarking was easily separated from the object image.

IV. Experiments

We carried out experiments to ensure the technology we propose was practical. The experiments focused on whether watermarking could be efficiently identified in the digital data with

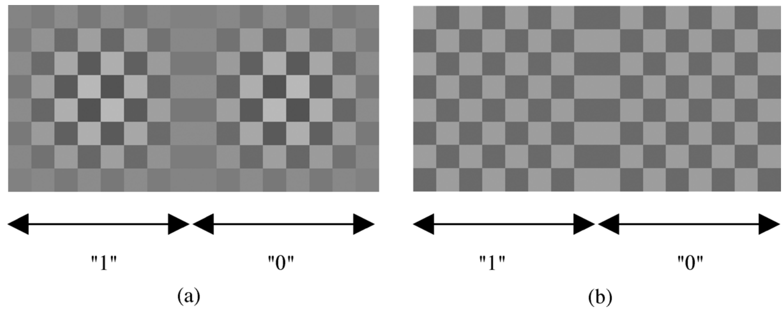


Fig. 3. Part of magnified image of watermarking with two blocks adjoining each other. (a) DCT $(\mathrm{DC} = 150, \mathrm{HC} = 25)$, (b) WHT $(\mathrm{DC} = 150, \mathrm{HC} = 25)$.

TABLE I
WALSH-HADAMARD MATRIX (a) 8×8 MATRIX, (b) 16×16 MATRIX

(a)

1	1	1	1	1	1	1	1
1	1	1	1	−1	−1	−1	−1
1	1	−1	−1	−1	−1	1	1
1	1	−1	−1	1	1	−1	−1
1	−1	−1	1	1	−1	−1	1
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)

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

which it was mixed from the object image, fulfilling the condition that it had to be sufficiently minute to be invisible on the object. Another focus was on its robustness against shooting conditions involving the use of digital cameras. To achieve these purposes, we evaluated the accuracy with which watermarking was read out, how invisible the watermarking image was, and what effect JPEG compression had on the photographed image data.

Watermarking images were produced that consisted of 16×16 blocks in this experiment, where each block had 8×8 pixels, i.e., the watermarking images had 128×128 pixels. Fig. 3 has part of a magnified image of watermarking. Binary watermarking information was embedded as blocks of “0” and “1”, and these were alternately positioned in a checkerboard pattern. A digital light processing (DLP) projector that had a resolution of 800×600 pixels was used as a light source. The watermarking images were projected onto pictures that were the objects, which were printed A4 images of the standard image data. The images in Fig. 4 were used for the pictures in the experiment. A white piece of paper was also used as a baseline. The values for DC and HC were changed and used as the experimental parameters. The size of the projected watermarking area was about 105×105 mm on the object image, which was equivalent to about 650×650 pixels taken with a digital camera that had a resolution of 4288×2848 pixels.

A rectangle was clipped out from the photographed image data as a watermarking area that was brighter than its neighbors, neglecting the geometrical distortion that occurs when it is beamed with a projector or when it is photographed with a digital camera. The resolution of the clipped rectangle was then transformed to just 256×256 pixels, and it was divided into 16×16 blocks each of which had 16×16 pixels. A forward orthogonal transform was then carried out on all blocks. In applying DCT, (6) was used as the forward transform

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

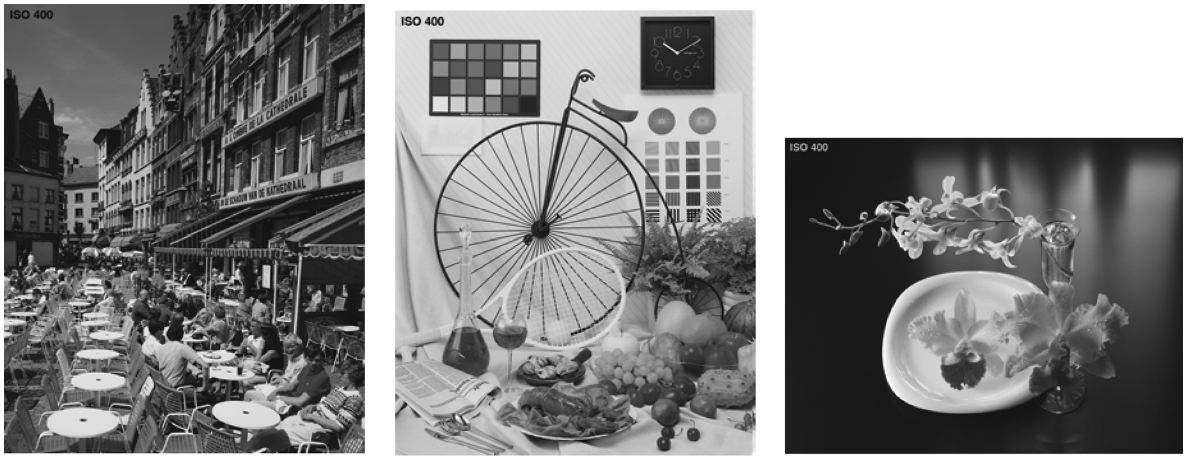
Here, $C(u)$ and $C(v)$ are the same as those in (1).

In applying WHT, (7) was utilized for the forward transform

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

where the values in Table I(b) were used as the components of matrix $\mathrm{wh}(i,j)$, and M is the number of pixels in the u- and$v$-directions in frequency space, which was 16 in this experiment.

The precision 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. Although the watermarking image embedded into the illumination consisted of blocks of 8×8 pixels, when the embedded data were read out, the blocks were converted to



SCID N2 SCI D N5 SCID N6

Fig. 4. Images used in experiments.

(a) (b)

Fig. 5. Photograph on which image of watermarking was projected. (a) DCT $(\mathrm{DC} = 150, \mathrm{HC} = 15)$, (b) WHT $(\mathrm{DC} = 150, \mathrm{HC} = 15)$.

blocks of 16×16 pixels. This could prevent the highest frequency component from vanishing or decreasing due to pixel data possibly being resampled in the projector.

We evaluated two methods of embedding the data, where the first was the one-block approach in which 1-bit data were embedded in one block. With this method, 256 1-bit binary data were embedded in 16×16 blocks. The second was the majority method where the same 1-bit data were embedded in three blocks that were sufficiently separated from one another, and we determined whether their readout data were different using a majority decision. The latter was used to improve the accuracy with which the embedded data were read out. The distance between the blocks in this experiment was determined to be 5, and 75 one-bit binary data were embedded using 16×16 blocks.

We also subjectively and objectively evaluated the quality of the projected watermarked images. We subjectively evaluated an SCID N2 image projected with a watermarking image pattern. Fig. 5 shows a projected watermarking image where DCT and WHT were used. Six image-processing specialists who judged whether the pattern of watermarking could be visually identified participated in the subjective evaluations. This was done by alternately displaying the image projected with and without watermarking and the specialists observed this from a distance of 2 m for about 2 or 3 s. The DC value was fixed at 150, and that of the HC was varied from 5 to 15. We evaluated both DCT and WHT under these conditions.

We used the peak signal-to-noise ratio (PSNR) for the objective evaluations. The image data for measuring PSNR, where the HC value was assumed to be other than "0" where the area was illuminated, were cut from the image data of the picture taken with the digital camera. The reference image data were also cut from the area where the image data without an embedding watermark was illuminated. The PSNR was obtained from the reference-image data and the image data from the cut-out area of the embedded watermark.

The PSNR was calculated with (8)

$$\mathrm{PSNR} = -10\log_{10}\frac{\sum_{i,j}\{x_r(i,j) - x_p(i,j)\}^2}{255^2 N} \qquad (8)$$

where $x_r(i,j)$ is the pixel value of the reference image data, $x_p(i,j)$ is the pixel value of the image data from the area of the embedded watermark, and N is the number of pixels in the clipped area. Each pixel was 8 bits long.

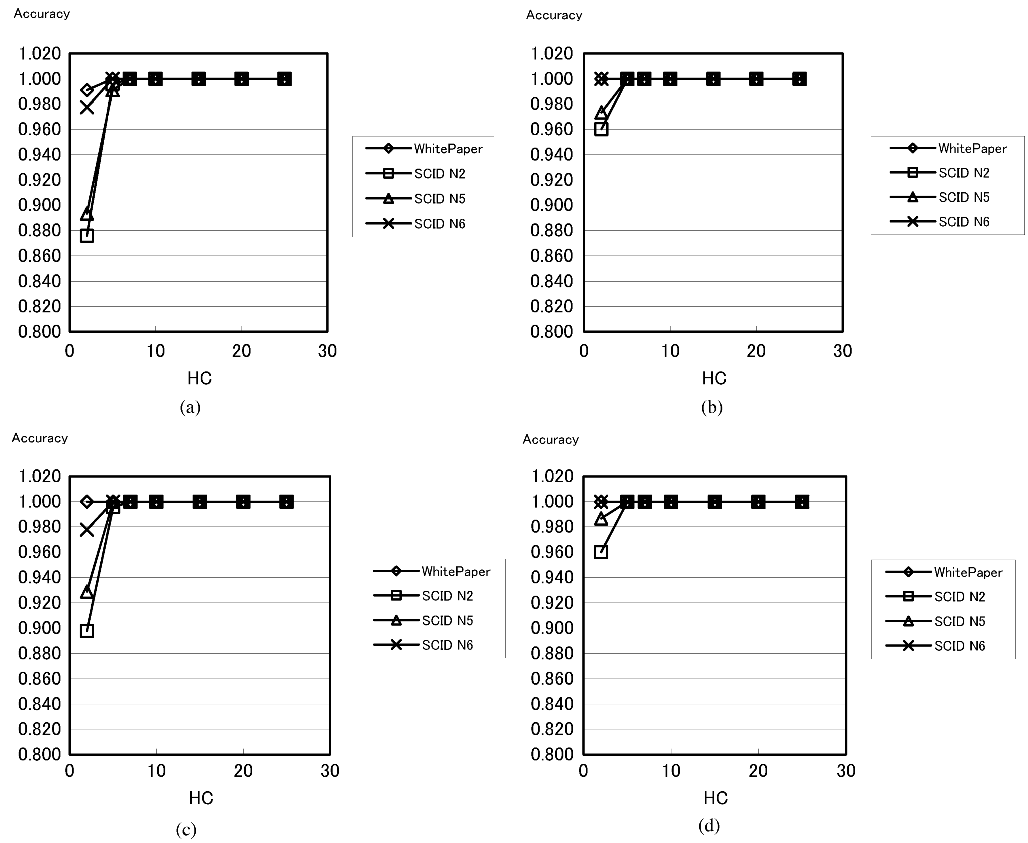


Fig. 6. (a) Accuracy of reading out data : DCT (1 block evaluation). (b) Accuracy of reading out data: DCT (Majority of 3-block evaluation). (c) Accuracy of reading out data : WHT (1 block evaluation). (d) Accuracy of reading out data: WHT (Majority of 3-block evaluation).

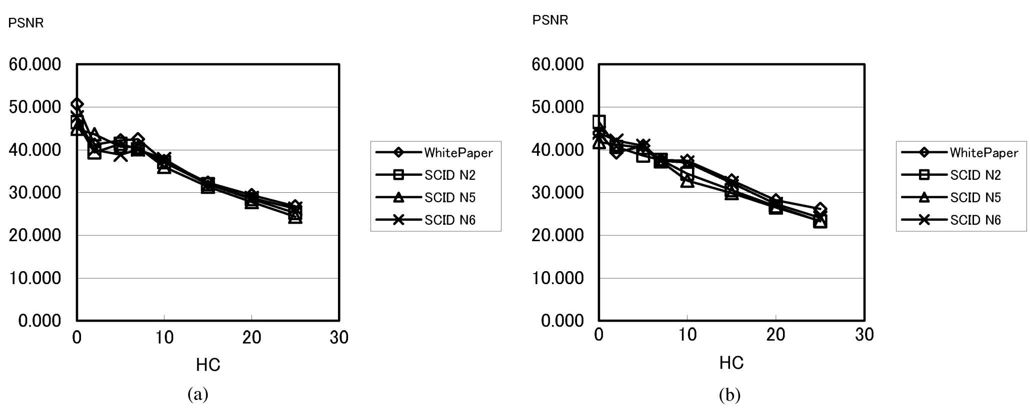


Fig. 7. (a) PSNR of watermark projected image (DCT), (b) PSNR of watermark projected image (WHT).

We also evaluated the effect of JPEG compression. The tolerance of image quality against degradation caused by JPEG lossy compression was evaluated by taking into consideration the general conditions when pictures are taken with a digital camera. The visual recognition of distortion due to JPEG lossy compression was generally difficult to detect at the compression rate of about 1/10 to 1/20 of non-compressed data. We evaluated the accuracy and PSNR of read-out image data that were expanded in this experiment after non-compressed image data were compressed into a volume of data that was about 1/20 that obtained by JPEG lossy compression.

V. Results and Discussion

Fig. 6(a)–(d) shows how precisely the embedded data were read out. The accuracy is indicated by the rate at which data were read out correctly from the entire body of data. There were 256 whole data for the one-block method and 75 for the majority approach. The DC value was fixed at 150, which was measured to be about 90.0 cd/m^2 when the watermarking images were projected onto the white piece of paper. We can see from Fig. 6 that accuracy with the one-block method was 100% at HC $= 7$ and over, and that with the majority method was 100% at HC $=$

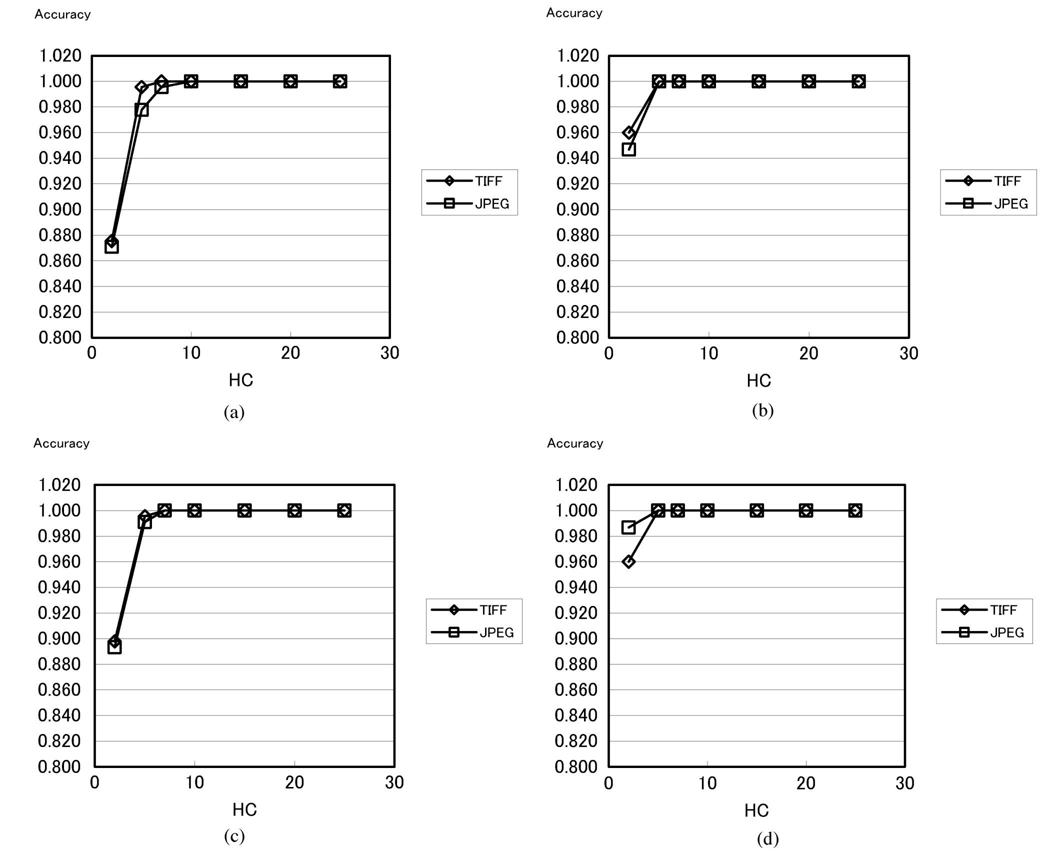


Fig. 8. (a) Effect of JPEG compression: Accuracy of reading out data: DCT (1 block evaluation). (b) Effect of JPEG compression: Accuracy of reading out data: DCT (Majority of 3-block evaluation). (c) Effect of JPEG compression: Accuracy of reading out data: WHT (1 block evaluation). (d) Effect of JPEG compression: Accuracy of reading out data: WHT (Majority of 3-block evaluation).

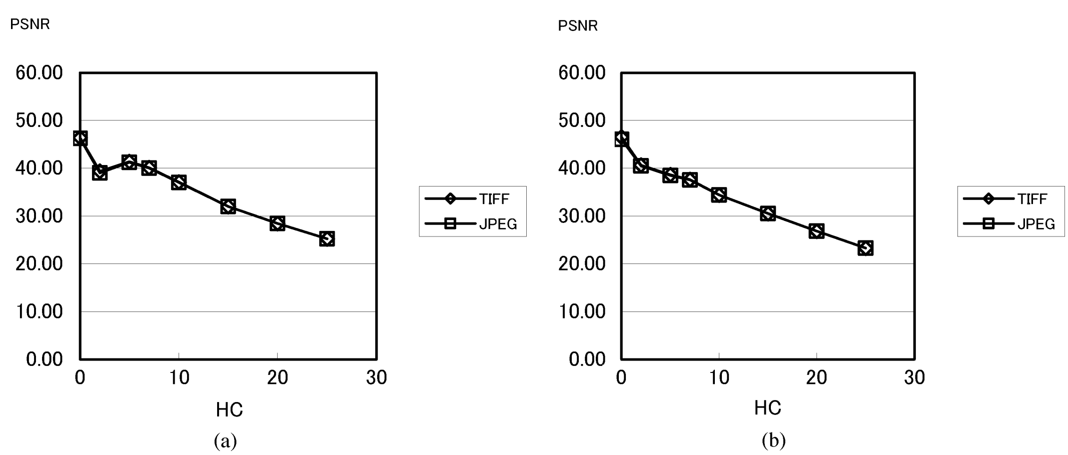


Fig. 9. (a) Effect of JPEG compression: PSNR of watermark projected image: DCT. (b) Effect of JPEG compression: PSNR of watermark projected image: WHT.

5 and over. These results were the same as those we obtained for DCT and WHT.

We concluded that accuracy with the one-block and majority methods was almost the same as that with DCT and WHT. As seen in Fig. 3, the pattern of the watermarking image projected onto the object image differs quite remarkably between DCT and WHT. With WHT, two pixel values are simply and alternately repeated, while with DCT, the amplitude of pixel values increases around the center of the 8×8 pixel block and reduces around its edge. However, the results obtained from the experiment indicated that the watermark could be detected even with such a characteristic watermark-image pattern, i.e., under an irradiance of watermarking of $\mathrm{HC} = 5$ or more for $\mathrm{DC} = 150$.

Fig. 7(a) and (b) plots the PSNR of the projected watermarked image. Under conditions of $\mathrm{HC} = 7$ or less, a PSNR of 40 dB or more was approximately indicated with DCT while a value of 38 dB or more was approximately indicated with WHT, even though the value was not necessarily a monotonic decrease. A tendency to monotonically decrease was indicated with DCT and WHT under conditions of $\mathrm{HC} = 10$ or more. A difference in the PSNR was seen in the object images in both cases. The PSNR was measured as the margin of error between two image data, which were taken under different watermarking-irradiance conditions and where an area was cut that was considered to be the same area. As the pixel positions in two of the image data did not completely correspond because of this, the PSNR for $\mathrm{HC} = 0$ (i.e., without watermarking) was a finite value. Moreover, the value for the region from $\mathrm{HC} = 2$ to 7 and the region for $\mathrm{HC} = 10$ and over indicated different tendencies. It seems reasonable to conclude that these originated from nonlinearity due to the characteristics of the projector and the change in the shooting conditions.

Six image-processing specialists subjectively evaluated whether they were able to visually recognize the watermarking pattern by observing the projected watermarked image. With DCT, no observers stated that they could identify the pattern at $\mathrm{HC} = 5$ or $\mathrm{HC} = 7$, three out of the six stated they could distinguish it at $\mathrm{HC} = 10$, and four stated they could spot it at $\mathrm{HC} = 15$. With WHT, no observers stated they could make out the pattern at $\mathrm{HC} = 5$, three stated they could differentiate it at $\mathrm{HC} = 7$, two stated they could identify it at $\mathrm{HC} = 10$, and five stated they could distinguish it at $\mathrm{HC} = 15$. The results from the subjective evaluations demonstrated that, under the $\mathrm{HC} = 5$ condition, the watermarking pattern was invisible with DCT and WHT, and under conditions of $\mathrm{HC} = 7$ or over, DCT was slightly superior to WHT in making the watermark pattern disappear. As shown in Fig. 3, the watermarking-image pattern with WHT was a simple repetition of two pixel values; otherwise with DCT, the pixel values decreased around the edges of the blocks. Therefore, the boundary parts of the blocks with WHT could be more easily recognized than with DCT. However, the results were reversed with $\mathrm{HC} = 7$ and $\mathrm{HC} = 10$ with WHT, and it seems possible that the nonlinear characteristics of the projector affected the results and it will therefore be necessary in future to rigorously set the evaluation conditions.

Fig. 8(a)–(d) shows what effect JPEG compression had on the accuracy of read-out data. This was evaluated by using SCID N2 as an object image only for $\mathrm{DC} = 150$. There were no great differences in accuracy between the JPEG-compressed and non-compressed (TIFF) images under either condition. Moreover, the difference in PSNR in both images was very small as indicated by Fig. 9(a) and (b). The evaluation conditions for measuring PSNR were also $\mathrm{DC} = 150$ and image SCID N2 was used. Comparable results were obtained when the white paper, SCID N5, and N6 were assumed to be the object image, and image degradation barely influenced these results at a compression rate of about 1/20 where almost no distortion occurred due to JPEG lossy compression.

As previously mentioned, although there is a possibility that DCT excelled in making the watermarking pattern invisible, further scrutiny is necessary after the subjective-evaluation conditions are tightened. Results other than those from the subjective evaluations seemed to be almost the same as those for DCT and WHT. We found DCT and WHT were not distinctly different in terms of the efficiency of watermarking as a result of these experiments. From the point of view of implementation cost and processing speed, WHT is superior to DCT. However, as recent microprocessor technology has provided strong functionality for multimedia data processing, DCT has also demonstrated that it is sufficiently practical for the illuminated watermarking we propose.

VI. CONCLUSION

We proposed an innovative method of watermarking using illumination that contains invisible information. It can prevent the illegal use of captured images of objects that have been difficult to protect with the conventional watermarking technology. We used DCT and WHT as orthogonal transforms to produce the watermarking image. We conducted experiments where one-bit binary data were embedded in one block that consisted of 8×8 pixels using the the highest-frequency component with i-DCT and i-WHT. The experimental results revealed that the accuracy with which the embedded data were read out reached 100% for 75 data using the majority method in both DCT and WHT. Our evaluation of the invisibility of the projected watermarking image revealed that the watermarking was hardly visible under the condition where the data were read out with 100% accuracy. JPEG compression under standard shooting conditions with a digital camera did not affect the results of the experiments. As a result, we demonstrated the practical feasibility of the technology we propose. Various orthogonal transforms other than DCT and WHT may be alternate methods of embedding watermarking into illumination. This is the next issue we intend to address.

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