LETTER

Number of Detectable Gradations in X-Ray Photographs of Cavities Inside 3-D Printed Objects

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SUMMARY We evaluated a technique for protecting the copyright of digital data for 3-D printing. To embed copyright information, the inside of a 3-D printed object is constructed from fine domains that have different physical characteristics from those of the object’s main body surrounding them, and to read out the embedded information, these fine domains inside the objects are detected using nondestructive inspections such as X-ray photography or thermography. In the evaluation, copyright information embedded inside the 3-D printed object was expressed using the depth of fine cavities inside the object, and X-ray photography were used for reading them out from the object. The test sample was a cuboid 46 mm wide, 42 mm long, and 20 mm deep. The cavities were 2 mm wide and 2 mm long. The difference in the depths of the cavities appeared as a difference in the luminance in the X-ray photographs, and 21 levels of depth could be detected on the basis of the difference in luminance. These results indicate that under the conditions of the experiment, each cavity expressed 4 to 5 bits of information with its depth. We demonstrated that the proposed technique had the possibility of embedding a sufficient volume of information for expressing copyright information by using the depths of cavities.

key words: digital fabrication, 3-D printing, 3-D printer, copyright protection, digital watermarking

1. Introduction

Three-dimensional (3-D) printers have become popular with consumers. People who have them can easily fabricate products by simply obtaining the digital data needed for 3-D printing. Hence, many people believe that 3-D printers will change the ways in which products are manufactured and physically distributed in the near future [1], [2].

However, such benefits of 3-D printers mean that anyone can easily manufacture bootleg products if he or she abuses the digital data for 3-D printing. Such copyright violations would obviously cause serious economic damage. Thus, techniques to protect the copyrights of digital data for 3-D printing are essential for the healthy development of markets for 3-D printers.

Although techniques to prevent illegal copying or illegal printing are of course important for protecting the copyrights of digital data for 3-D printing [3]–[6], techniques that reveal such violations are also crucial in cases in which violations occur. Digital watermarking is commonly used to reveal copyright violations affecting all kinds of digital data; however, conventional techniques can only embed watermarks in the digital data, not in the actual objects fabricated with 3-D printers. Copyright information needs to be embedded in the fabricated objects so that the information can be read to reveal any violation. For example, suppose a company that is not allowed to use digital data held by the copyright holder sells illegally fabricated objects. In this case, the copyright holder can expose the company by detecting the copyright information embedded in the sold objects and can assert his or her just rights. Thus, techniques to reveal copyright violations, i.e., techniques to embed copyright information in fabricated objects and have the information be readable, are essential for protecting the copyrights of digital data for 3-D printing.

Previous studies proposed techniques that could embed information in fabricated objects and read it out from them [7], [8]. In these techniques, “tags” or “codes” that could be read by terahertz time-domain spectroscopy or X-ray computed tomography were used for embedding information inside fabricated objects. Because terahertz time-domain spectroscopy or X-ray computed tomography could read the tags or codes inside fabricated objects, the information could be read out from the objects. However, the technique with terahertz time-domain spectroscopy or X-ray computed tomography could not be read by terahertz time-domain spectroscopy or X-ray computed tomography. The technique with X-ray computed tomography embedded information inside the fabricated objects by using QR codes that required square areas.

We previously proposed and evaluated a technique for protecting copyrights of digital data for 3-D printing [9], [10]. In this technique, copyright information is first embedded in the digital data. Then, this information is also embedded in the objects when they are being fabricated. The embedded information is expressed using ASCII and encoded by constructing fine domains inside the object that have different physical characteristics from the surrounding main body of the object. For example, the existence or nonexistence of fine domains at designated positions can represent “0” or “1.” The fine domains are detected using nondestructive inspections such as X-ray photographs or thermography to read out the copyright information from the objects.

In our previous studies, small cavities were used as the fine domains, and the copyright information was read out from the fabricated objects. The fine domains were formed at the same time as the main body, and square areas were not re-

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quired because the designated positions could be distributed throughout the object.

However, we have yet to evaluate the information volume that the proposed technique can embed in a fabricated object. Such an evaluation is crucial because, if the information volume were insufficient to express copyright information, the technique would be of no practical use. Embedding even a simple copyright notice, e.g., “2016 (c) Masahiro Suzuki,” requires around 200 bits. Thus, we need to evaluate the information volume.

Consequently, this paper presents an evaluation of the possibility that the proposed technique can embed a sufficient volume of information for expressing copyright information. In the evaluation, copyright information was expressed using the depth of fine cavities inside a fabricated object, and X-ray photography were used for reading them out from the object. As the luminance in the photographs depended on the transmittance of the X-rays, the differences in the depths of the cavities appeared as differences in luminance. That is, the depths of the cavities could be used to express the embedded information; therefore, the evaluation assessed the range of depths that could be detected with X-ray photography.

2. Methodology

We took X-ray photographs of a fabricated object that had cavities of different depths inside it and examined the range of depths that could be detected from the photographs. The different depth levels expressed different pieces of information; e.g., the first level expressed “0,” and the second level expressed “1.” Thus, the detectable depths determined the information volume.

The differences between the depths of the cavities appeared as the differences in the luminances of pixels in the photographs; therefore, the depths of the cavities could be detected if the differences in luminance between cavities were larger than the differences in luminance within the cavities. A 99% confidence interval of luminance, which represented the difference in luminance within the cavities, was calculated for the individual depth levels. This interval indicates that the mean luminance would appear within the interval at 99% probability when this experiment was replicated. Therefore, when this interval did not overlap the neighboring levels of depth, the depth level was considered to be detectable.

2.1 Materials

A black cuboid made from a rigid opaque photopolymer (VeroBlack, Stratasys Ltd., Eden Prairie, MN) was fabricated with an inkjet 3-D printer (Objet 30, Stratasys Ltd., Eden Prairie, MN). The cuboid was 46 mm wide, 42 mm long, 20 mm deep, and contained 47 cavities that were 2 mm wide and 2 mm long (Fig. 1). The depths of the cavities inside the cuboid ranged from 0.5 to 18.0 mm, and the step size was 0.5 or 1.75 mm.

A microfocus X-ray computed tomography system (in-speXio SMX-225CT, Shimadzu Corporation, Kyoto, Japan) was used to take the X-ray photographs (Fig. 2). A single X-ray beam entered the cuboid from the top surface, and the transmitted beam was received by an imaging plate below the bottom surface. As the beam generator was positioned just above the center of the cuboid, the angle of incidence was orthogonal in the center, but was non-orthogonal in the periphery.

2.3 Method of Analyzing X-Ray Photographs

The contrast in luminance of the photograph was first visually adjusted so that it would be suitable for analysis. One of the authors conducted this adjustment. He finished the adjustment when he determined that as many depths as possible could be detected.

The luminance flatness of the photograph was also measured in four directions (see Fig. 4) to evaluate shading compensation. The luminance of individual pixels was plot-
ted as a function of position except for the cavity areas. The necessity for shading compensation was assessed on the basis of these functions.

The mean luminance and 99% confidence interval for each cavity were then calculated. A window, which was 35 pixels wide and 35 pixels long, was scanned through each cavity, which was 45 pixels wide and 45 pixels long. The mean luminance for each scan window was calculated; that is, there were 100 mean luminances for each cavity. The mean luminance for each cavity was calculated from the 100 mean luminances. The 99% confidence interval for each cavity was also calculated from the 100 mean luminances.

3. Results

Figure 3 shows a photograph whose luminance contrast was adjusted. The highest and lowest luminances were 235 and 100. The luminance resolution was sufficient to analyze the photograph.

Figure 4 plots the results for luminance flatness except for the cavity areas. The correlation coefficients ($r$), which indicate the relationship between the position and luminance, in all four directions were close to zero (horizontal: $r = -0.04$; vertical: $r = -0.05$; top-left to bottom-right: $r = 0.12$; top-right to bottom-left: $r = -0.18$). That is, the luminance did not depend on the positions. These results indicated that luminance flatness was sufficient and that shading compensation was unnecessary.

Table 1 summarizes the highest luminance and lowest luminance of the 99% confidence interval for each cavity depth. No depth intervals from 0.5 to 10.5 mm overlapped neighboring intervals. These results indicated that these cavities, the depths of which were from 0.5 to 10.5 mm, were suitable for embedding information and that these 21 levels of depth could be detected when these cavities were used to embed information.

4. Discussion

According to the results obtained from the experiment, we could express 4 to 5 bits by using the depths of each cavity under the conditions in the experiment. When each depth level represented one numerical value, the 21 levels of detectable depth represented 21 numerical values, i.e., 4 to 5 bits of information. Note that this information volume was for one cavity. The information volume can be increased by using multiple cavities. These findings mean that it’s possible to express sufficient information for practical use.

Here, we take the case of embedding “2016 (c) Masahiro Suzuki,” which is the example of simple copyright information described in Sect. 1, to consider the importance of the findings in this study. When the existence or nonexistence of cavities is used to embed information, 192 cavities

<table>
<thead>
<tr>
<th>Depths of cavities (mm)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest luminance</td>
<td>205.3</td>
<td>199.6</td>
<td>193.8</td>
<td>190.5</td>
<td>186.5</td>
<td>182.4</td>
<td>174.9</td>
<td>171.9</td>
<td>166.2</td>
</tr>
<tr>
<td>Lowest luminance</td>
<td>204.9</td>
<td>199.3</td>
<td>193.2</td>
<td>190.0</td>
<td>185.8</td>
<td>181.6</td>
<td>173.9</td>
<td>170.8</td>
<td>165.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depths of cavities (mm)</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
<th>8.5</th>
<th>9.0</th>
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<tr>
<td>Highest luminance</td>
<td>164.8</td>
<td>161.7</td>
<td>157.7</td>
<td>151.7</td>
<td>147.2</td>
<td>144.0</td>
<td>142.8</td>
<td>139.4</td>
<td>136.4</td>
</tr>
<tr>
<td>Lowest luminance</td>
<td>163.9</td>
<td>160.7</td>
<td>156.7</td>
<td>150.7</td>
<td>146.0</td>
<td>142.8</td>
<td>141.8</td>
<td>138.1</td>
<td>135.1</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Depths of cavities (mm)</th>
<th>9.5</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
<th>12.0</th>
<th>12.5</th>
<th>13.0</th>
<th>13.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest luminance</td>
<td>132.1</td>
<td>126.8</td>
<td>123.5</td>
<td>129.0</td>
<td>131.9</td>
<td>129.4</td>
<td>116.0</td>
<td>112.1</td>
<td>111.6</td>
</tr>
<tr>
<td>Lowest luminance</td>
<td>130.7</td>
<td>125.4</td>
<td>122.2</td>
<td>127.8</td>
<td>130.2</td>
<td>128.7</td>
<td>114.2</td>
<td>111.2</td>
<td>110.8</td>
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</table>

<table>
<thead>
<tr>
<th>Depths of cavities (mm)</th>
<th>14.0</th>
<th>14.5</th>
<th>15.0</th>
<th>15.5</th>
<th>16.0</th>
<th>16.5</th>
<th>17.0</th>
<th>17.5</th>
<th>18.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest luminance</td>
<td>111.6</td>
<td>107.0</td>
<td>112.5</td>
<td>108.9</td>
<td>102.5</td>
<td>109.9</td>
<td>102.1</td>
<td>104.7</td>
<td>111.9</td>
</tr>
<tr>
<td>Lowest luminance</td>
<td>109.6</td>
<td>106.2</td>
<td>108.9</td>
<td>104.4</td>
<td>99.3</td>
<td>103.3</td>
<td>98.4</td>
<td>102.3</td>
<td>109.4</td>
</tr>
</tbody>
</table>
are required because one cavity represents only 1 bit. Although the inside of an object can be constructed with this number of cavities, a large area is required for the construction. However, when one cavity expresses 4 bits in terms of its depth, only 48 cavities are required, and the area for constructing these cavities is a quarter of that in the above case. Thus, the findings in this study are very important for embedding copyright information in fabricated objects under practical circumstances.

Although depths deeper than 11 mm were unable to be detected, they would be detectable if the X-ray photographs were taken with a different method from the one used in this study. We considered that the non-perpendicularly transmitted beam through the receptor (see Sect. 2.2 and Fig. 2) caused large differences within deep cavities. That is, the side walls of the deep cavities were projected onto the photographic plate because of their depth, so that the differences within deep cavities increased. Hence, if the generator could have projected a perpendicular beam at every position onto the plate, deeper depths would have been detectable.

As the luminance in X-ray photographs depends on the X-ray transmittance of material and the strength of the X-rays, the findings from this study can be applied to different materials with cavities of different depths from those in this study. When transmittance is lower, stronger X-rays are required to detect differences in cavity depth. Conversely, weaker X-rays are required when the transmittance is higher. Thus, the difference in cavity depth could be detected by adjusting X-rays to a suitable strength.

Techniques to decode information expressed in terms of cavity depth have yet to be assessed, but we intend to do this in the future. As described in the first paragraph of this section, one depth level corresponds to one number; therefore, the decoding system needs to detect the absolute depth. Although the results described in Sect. 3 only indicated that relative depths could be detected, cavities with staircase shapes would help to detect absolute depth because the system could use this shape as a reference for the absolute depth (see Fig. 1). We intend to study this kind of detection in the near future.

5. Conclusion

We evaluated our technique of protecting copyrights of digital data for 3-D printing. In this technique, fine cavities are constructed inside 3-D printed objects to embed copyright information, and the embedded information is nondestructively read with X-ray photography. In the evaluation, X-ray photographs were taken of test samples that had cavities with different depths, and they were examined to see the detectable depths. The test sample was a cuboid 46 mm wide, 42 mm long, and 20 mm deep. The cavities were 2 mm wide and 2 mm long. The results obtained from the experiment indicate that 21 levels of depth could be detected, and that 4 to 5 bits of information could be expressed by the depth of each cavity under the conditions of the experiment. We demonstrated that the technique has the possibility of embedding a sufficient volume of information for expressing copyright by using the depths of the cavities.

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References