Technique for Protecting Copyrights of Digital Data for 3-D Printing, and Its Application to Low Infill Density Objects

Masahiro Suzuki, Piyarat Silapasuphakornwong, Hideyuki Torii, Hiroshi Unno, Kazutake Uehira
Kanagawa Institute of Technology
Atsugi, Japan
E-mail: msuzuki@ctr.kanagawa-it.ac.jp, silpiyarat@gmail.com, torii@nw.kanagawa-it.ac.jp, unno@nw.kanagawa-it.ac.jp, uehira@nw.kanagawa-it.ac.jp

Youichi Takashima
NTT Service Evolution Laboratories
Nippon Telegraph and Telephone Corporation
Yokosuka, Japan
E-mail: takashima.youichi@lab.ntt.co.jp

***Abstract*— We evaluated our previously proposed technique to protect copyrights of digital data for 3-D printing. The technique embeds copyright information into not only digital data but also fabricated objects and enables the information to be reads to reveal possible copyright violations. In this study, copyright information was embedded into low infill density objects by constructing their inside with high infill density areas, and thermography was used for readout. An experiment was conducted to examine whether high infill density areas can be recognized from thermal images. The results indicated that they can be. We demonstrated that our technique is applicable to low infill density objects.**

Keywords-digital fabrication; 3-D printing; 3-D printer; copyright; digital watermarking.

I. INTRODUCTION

Three-dimensional (3-D) printers have become popular with consumers. People who have 3-D printers can easily fabricate products by simply obtaining the digital data for 3-D printing. Hence, many people believe that 3-D printers will change the ways in which manufacturing and physical distribution will be carried out 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 digital data for 3-D printing. Such copyright violations will 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 to protect the copyrights of digital data for 3-D printing [3]–[6], techniques to divulge such violations are additionally crucial in cases in which these violations occur. Digital watermarking is common to all kinds of digital data to disclose copyright violations; however, conventional techniques can only embed watermarks into digital data but not into actual objects fabricated with 3-D printers. Copyright information needs to be embedded into fabricated objects so that the information can be read to reveal any violations. For example, when a company that is not allowed to use digital data held by the copyright holder is selling illegally fabricated objects, the copyright holder can expose the company by detecting the copyright information embedded into the sold objects and can assert his or her just rights. Thus, techniques to reveal copyright violations, i.e., techniques to embed copyright information into fabricated objects and have the information be readable, are essential to protect the copyrights of digital data for 3-D printing.

We have previously proposed a technique to embed copyright information into fabricated objects and to have that information be readable and demonstrated its feasibility [7] [8]. With this technique, the inside of objects is constructed with small areas, which have physical characteristics that are different from the areas surrounding them, to embed the information. These small areas are detected using nondestructive inspections, such as X-ray photography or thermography, to reveal the embedded information. Our previous studies demonstrated that information embedded with small cavities inside objects can be read. Thus, information can feasibly be embedded into objects and be read.

Although we have evaluated our technique using objects fabricated with high infill density, i.e., 100% [7] [8], objects with low infill density are often fabricated for practical use. For example, when users want to save time or materials, they fabricate objects with low infill density. In our previous studies, we embedded copyright information into high infill density objects with small cavities inside because they did not have any other empty spaces; however, low infill density objects have many empty spaces inside, and embedding the information into them is difficult. Thus, methods applicable to low infill density objects are required for practical use with our technique.

This paper presents a method of applying our technique to low infill density objects. In Section 2, we first describe the basic concept of the technique and the principle of the methods previously applied to high infill density objects then describe the principle of our method for low infill density objects. In Section 3, we describe the methodology, explain the results, and provide discussion of an experiment to evaluate the feasibility of our method. In Section 4, we conclude the paper.

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II. Our Technique and Its Application to Low Infill Density Objects

Figure 1 is an illustration showing the basic concept of our technique. Digital data for 3-D printing are created with 3-D modeling software, such as 3-D CAD, and copyright information is embedded into the data. When actual objects are fabricated using the data, the information embedded into the data is also embedded into the objects. This information is made readable using nondestructive inspection, such as X-ray photography or thermography, which enable the detection of copyright violations, such as making bootleg products. Thus, the copyrights of digital data for 3-D printing are protected by embedding copyright information into not only digital data but also fabricated objects for readability.

Figure 2 is an illustration showing the principle of our technique. In our previous studies, copyright information, which was expressed using ASCII, was encoded with small cavities inside high infill density objects [7] [8]. For example, the existence and nonexistence of cavities at certain positions were represented as “0” and “1,” respectively (see Figure 2-A). The objects, which had cavities inside them, were heated using electric equipment, such as halogen lamps, and the surface temperature of the objects was measured using thermography (see Figure 2-B). The surface temperature at positions where the cavities existed became higher than that at other positions because the cavities blocked thermal flow (see Figure 2-B). Previous studies demonstrated that the existence or nonexistence of cavities can be detected from thermal images and that the embedded information can be decoded from the detected cavities [7] [8]. Thus, thermography can feasibly be used to read copyright information embedded into high infill density objects by constructing their insides with small cavities.

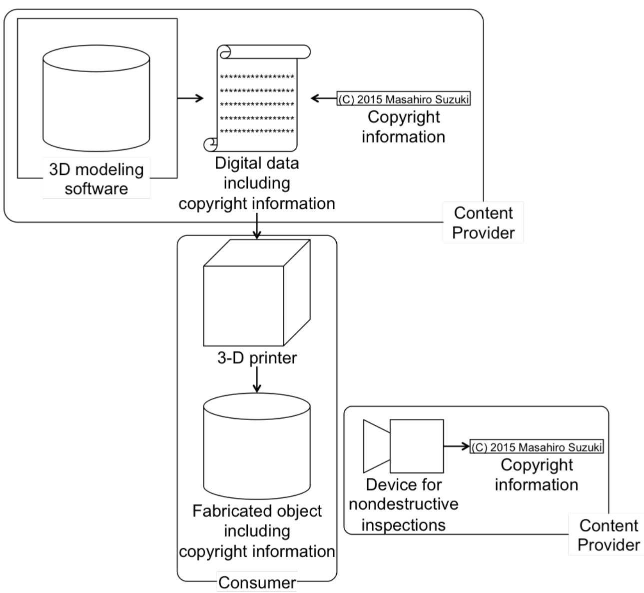

Figure 1. Illustration showing basic concept of our technique.

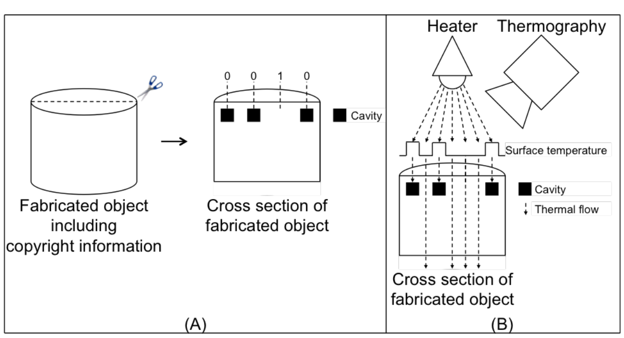

Figure 2. Illustration showing principle of our technique.

However, because low infill density objects have many empty spaces inside, the aforementioned method cannot be applied. For example, the low infill density objects shown in Figure 3 have a honeycomb structure inside, and each space inside the honeycomb is empty. If we embed copyright information into such objects with small cavities inside and heat them, the surface temperature in the cavities would not differ from other positions because not only the cavities but also the empty spaces would block thermal flow. Thus, other methods are required for applying our technique to low infill density objects.

We present a method for embedding copyright information into low infill density objects and having that information be readable. Figure 4 is an illustration showing the principle of this method. Copyright information expressed using ASCII is encoded with high infill density areas, i.e., pillars, inside low infill density objects. The

Figure 3. Photographs of inside low infill density objects.

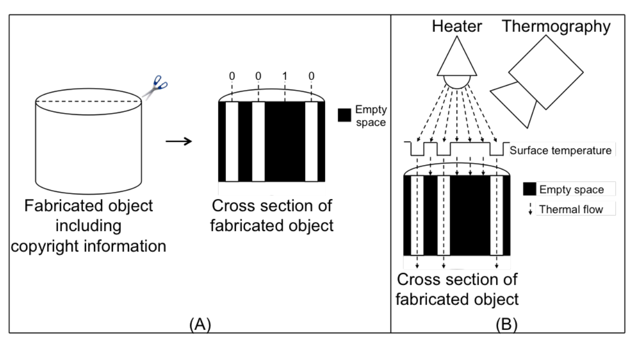

Figure 4. Illustration showing principle of method for applying our technique to low infill density objects.

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existence and nonexistence of the pillars is represented as "0" and "1," respectively. The objects are heated, and the surface temperature is measured using thermography. The surface temperature at the positions where the pillars exist becomes higher than that of the other positions because the pillars do not block thermal flow, even though empty spaces do. The existence or nonexistence of pillars is detected from thermal images, and the embedded information is decoded from the detected pillars. Thus, copyright information is embedded into low infill density objects by constructing their inside with high infill density areas and the information is made readable using thermography.

III. EXPERIMENT

A. Methodology

An experiment was conducted to examine whether high infill density areas, i.e., pillars, inside low infill density objects can be recognized from thermal images. The recognition rate was calculated using the following equation:

$$R_{\text{recognition}}(\%) = \frac{N_{\text{detected}}}{N_{\text{embedded}}} \times 100\,, \qquad (1)$$

where the $R_{\text{recognition}}$ is the recognition rate, the N_{embedded} is the number of existing or non-existing pillars used to embed copyright information, and N_{detected} is the number of existing or non-existing pillars correctly detected. The N_{detected} was determined by analyzing thermal images of two test samples, which were fabricated from black polylactic acid filament using a fused deposition modeling 3-D printer, i.e., a MakerBot Replicator. The first test sample had 1% infill density, and the second test sample had 10% infill density (see Figure 5). Each test sample had four arrays of pillars, and each array corresponded to each of four conditions: two conditions of pillar size (1 and 2 mm) × two conditions of space between the pillars (1 and 2 mm) (see Figure 6). In an analysis of the thermal images, a still image was extracted from a video image for each frame, and each still image was binarized using adaptive thresholding [9]. A logical disjunction among binarized images was calculated for each position where copyright information was embedded, and N_{detected} was defined as the number of positions where the logical disjunction accorded with the existing or non-existing pillar. The thermal images were taken using Testo 875. Two halogen lamps, positioned at 16 cm and 60 degrees left and right, were used to heat the test samples. In each trial of taking the thermal images, the test samples were first heated, then the lamps were turned off. The test samples were then cooled to their initial temperature. The thermal images from turning the lamps off were used for the analysis. Thus, the recognition of high infill density areas inside low infill density objects from thermal images was examined by calculating the recognition rate.

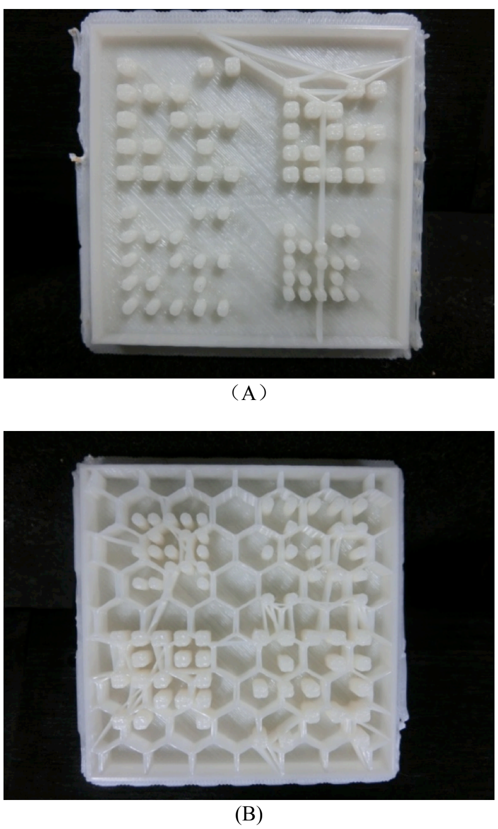


Figure 5. Photographs of inside test samples. (A) Inside of test sample whose infill density was 1%. (B) Inside of test sample whose infill density was 10%. Note that test samples actually used in experiment were black.

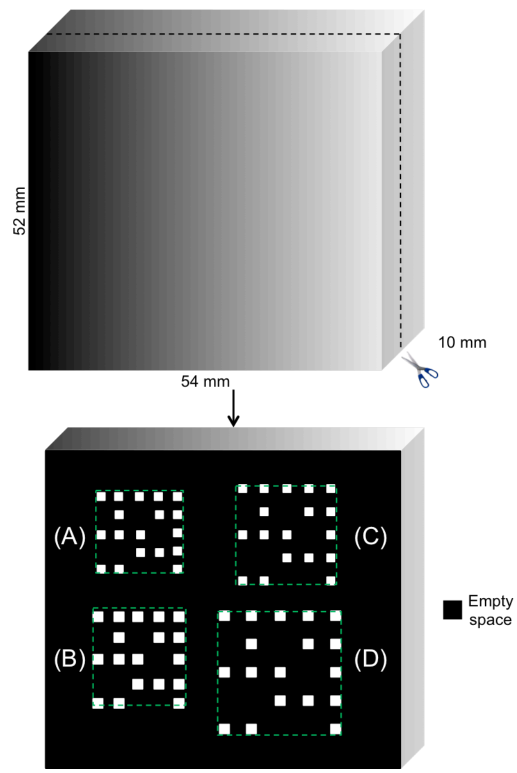
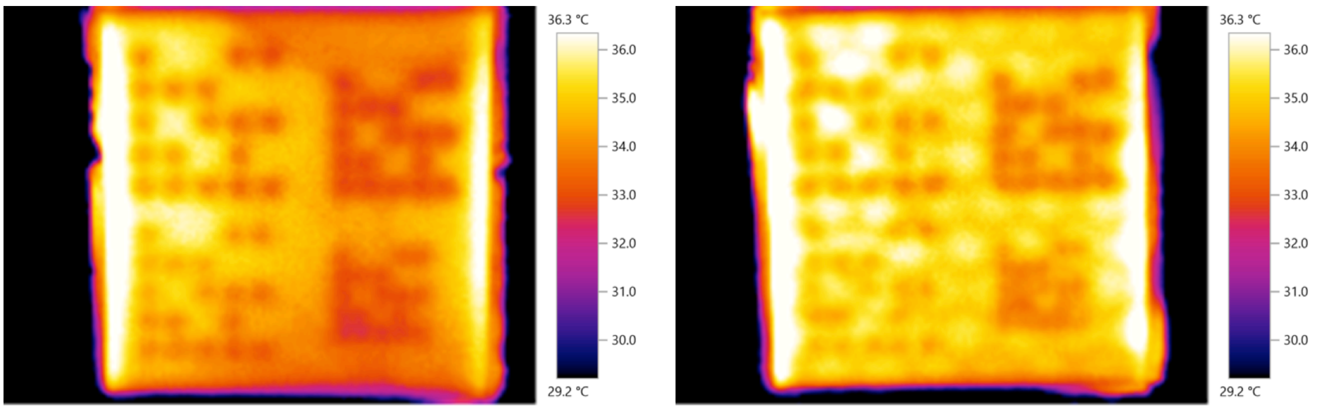


Figure 6. Schematic of test samples. (A) Array of pillars under 1-mm size × 1-mm space condition. (B) Array of pillars under 2-mm size × 1-mm space condition. (C) Array of pillars under 1-mm size × 2-mm space condition. (D) Array of pillars under 2-mm size × 2-mm space condition.



(A) (B)

Figure 7. Results of thermal images of test samples. (A) Thermal image of test sample whose infill density was 1%. (B) Thermal image of test sample whose infill density was 10%.

TABLE 1. RESULTS OF THE RECOGNITION RATE (%)

Infill density							
1%				*10%*			
Size				**Size**			
1 mm		*2 mm*		*1 mm*		*2 mm*	
Space		**Space**		**Space**		**Space**	
1 mm	*2 mm*	*1 mm*	*2 mm*	*1 mm*	*2 mm*	*1 mm*	*2 mm*
100	100	100	100	88	100	96	100

B. *Results and Discussion*

Figure 7 shows the thermal images, and Table 1 summarizes the recognition rate. All four arrays were completely recognized under the 1% condition, and the two arrays with the 2-mm space were completely recognized under the 10% condition. These results suggest that copyright information can be embedded into low infill density objects by constructing their inside with high infill density areas and be readable using thermography. Thus, our technique can feasibly be applied to low infill density objects.

IV. CONCLUSION

We evaluated our technique to protect copyright information of digital data for 3-D printing. This technique embeds copyright information into low infill density objects by using our method of constructing their inside with high infill density areas and makes the information readable using thermography. We conducted an experiment to examine whether high infill density areas inside low infill density objects can be recognized from thermal images. The results indicated that they can be. Thus, we demonstrated that our technique is feasible.

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