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Stencil-based 3D facial relief creation from RGBD images for 3D printing

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Three-dimensional (3D) selfie services, one of the major 3D printing services, print 3D models of an individual's face via scanning. However, most of these services require expensive full-color supporting 3D printers. The high cost of such printers poses a challenge in launching a variety of 3D printing application services. This paper presents a stencil-based 3D facial relief creation method employing a low-cost RGBD sensor and a 3D printer. Stencil-based 3D facial relief is an artwork in which some parts are holes, similar to that in a stencil, and other parts stand out, as in a relief. The proposed method creates a new type of relief by combining the existing stencil techniques and relief techniques. As a result, the 3D printed product resembles a two-colored object rather than a one-colored object even when a monochrome 3D printer is used. Unlike existing personalization-based 3D printing services, the proposed method enables the printing and delivery of products to customers in a short period of time. Experimental results reveal that, compared to existing 3D selfie products printed by monochrome 3D printers, our products have a higher degree of similarity and are more profitable.

KEYWORDS

3D Printing, relief, RGBD Image, stencil, stencil-based relief

1 | INTRODUCTION

Three-dimensional (3D) printing refers to the process of creating real objects from digital 3D models by continuously stacking very thin layers of material, that is, it creates actual products from digital objects such as computer-aided design models. Various types of 3D printing technologies, such as stereo lithography, laser melting, fused deposition modeling (FDM), digital light processing (DLP), and inkjet, have been developed. Materials such as plastics, metals, ceramics, paper, biochemical tissues, and food, can be used in 3D printing.

Various applications employing 3D printing technology have been proposed and developed. Rapid prototyping speeds up the early stages of product development by enabling the quick manufacturing and evaluating of prototypes of products to obtain optimal solutions more quickly and efficiently. This process saves time and money, and increases the reliability of the products in later stages of product development. Rapid prototyping is the most popular application of 3D printing and is widely utilized in industries such as the medical, dental, aerospace, automotive, construction, jewelry, art, and fashion industries.

A significant advantage of 3D printing is mass customization, that is, the production of a series of personalized goods such that products differ while maintaining low production prices through the use of mass production [1]. 3D printing for customization and small quantity batch productions is expected to replace traditional manufacturing methods and change lives. Additionally, many new business opportunities have been proposed owing to the ability to customize and personalize 3D printing processes. These include jewelry and souvenir printing, jewelry models with customized designs, customized video games, 3D printed action figures and popular animation characters, 3D printed selfie services, 3D printed custom prosthetics and assistive devices, 3D printing bakeries, and 3D printed personalized gifts.

Existing services that print and sell personalized products require expensive precision scanners and full-color 3D printers. For example, 3D selfie services utilize the personalization capabilities of 3D printing, which scan a person's entire body and print it as a figure. The service requires scanner systems consisting of dozens of cameras and expensive 3D printers capable of full-color printing. However, to scan the body or face of a customer, the customer has to visit a studio.

Moreover, the time required for the 3D printing of these products is significantly higher than that required for the method proposed in this paper. Therefore, after placing an order, a customer has to wait for a long time to receive the finished goods. Personalization-based 3D printing services that have thus far been commercialized face high business barriers owing to their high cost. Moreover, the high prices of printed products limit their expansion in the market.

In recent years, 3D printing has emerged as a technology that is easily accessible to individuals and small- and large-sized enterprises. Smaller 3D printers costing less than $1000 have begun to appear on the market owing to the increasing demand for 3D printer manufacturing. Low-cost RGBD sensors, such as Kinect, make it possible to scan any object without the use of professional precision 3D scanners. The aforementioned scanners and 3D printers allow users to easily manufacture personalized products.

However, low-cost scanners such as Kinects cannot capture accurate geometric information of objects. Therefore, it is not suitable to use them to scan sensitive objects such as human faces. Most low-cost 3D printers have similar quality problems. Most FDM printers, which are a type of low-cost 3D printer, are monochromatic and only capable of printing objects in a single color. This is not a problem when the printed objects are internal parts whose shapes are more important than their appearances. However, it is very difficult to print objects such as human faces, where the appearance of the face is important, because the printed object does not possess the rich color of human faces.

In this paper, we propose a new stencil-based 3D facial relief creation system involving a low-cost scanner and a 3D printer. A stencil-based 3D facial relief is a facial artwork in which some parts are holes, similar to that in a stencil, and other parts stand out, as in a relief. The proposed method combines existing stencil techniques and relief techniques. First, a binary stencil image is generated by partitioning the pixels of the human facial image acquired from a low-cost scanner, such as Kinect, into two regions based on a specific criterion. Second, the pixels of a specific color (eg, a dark color) are discarded, and the remaining pixels are elevated by utilizing the depth of each pixel to generate a 3D relief model. Finally, the 3D face relief is completed by printing the relief model.

Even though the relief model is printed by using a low-cost, single-color 3D printer, it exhibits a visual effect that is represented in two different colors similar to that in stenciled pictures. In addition, because it possesses a 3D form rather than a conventional flat stencil, it provides a more stereoscopic feeling. The experimental results reveal that the 3D facial reliefs created by the proposed method are more valuable than those created using existing approaches in terms of aesthetics and cost when using the same low-cost scanner and 3D printer.

From a technical point of view, the main contribution of the proposed method is that it is the first method, to the best of the authors' knowledge, that combines a stencil technique and a relief technique to manufacture 3D facial reliefs from images and somewhat coarse 3D models obtained from the Kinect sensor. Artwork printed via the proposed method resembles a two-colored object rather than a one-colored object even though a monochrome 3D printer is used. From a business point of view, unlike existing personalization-based 3D printing services, the proposed 3D printing service enables the delivery of products to the customers in a short period of time. Such a product can be printed quickly because it is composed of a single color, and approximately half of the product comprises of empty space.

The rest of this paper is organized as follows. We describe previous related studies in Section 2 and explain our proposed system in Section 3. We describe the experimental results in Section 4. Finally, the conclusions of the study are provided.

2 | RELATED WORK

Stencils are thin sheets of cardboard, plastic, or metal with patterns or letter shapes cut out. They are used to produce the cut-out design on the surface placed underneath them by the application of ink or paint through the holes. One of the advantages of stencils is that they can be reused repeatedly and rapidly produce identical letters or designs. To be reused, stencils must remain intact after a design is produced and the stencil is removed from the work surface. For some designs, this is achieved by connecting stencil islands (sections of material that are inside the cut-out “holes” in the

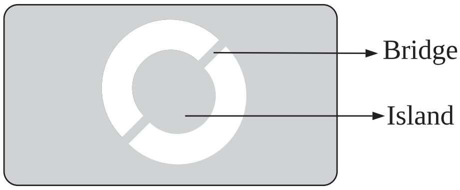

FIGURE 1 Parts of a stencil

stencil) to other parts of the stencil via bridges (narrow sections of material that are not cut out), as shown in Figure 1.

From an artistic point of view, a stencil is a means of abstractly expressing an object in two colors. Figure 2 shows facial stenciled images that are based on this feature.

Stencil generation techniques are used in the artistic domain as well as in fields such as cartoon rendering [2], half-tone rendering [3], and optical arts [4], which generate non-realistic scenes.

Bronson and others created a stencil image from an image or 3D mesh through the following steps [5]. First, they conducted a two-tone cartoon rendering on a 3D mesh and applied a silhouette line drawing to the rendered image to obtain a final black and white image. Second, they applied a simple filling algorithm to identify the islands that had to be connected to each other, and then constructed a graph structure in the following manner: Nodes corresponding to islands were created, and an edge was added between two islands if a bridge could be placed between them without any interference from the other islands. The distance to the edge was determined by considering the bridge length and the curvatures of the island boundaries where the bridge was placed. Then, the edges were selected, and the bridges were placed in the same manner as that used in the selection of edges while building a minimum spanning tree.

Igarashi and others [6] conducted a study to create an interactive stencil image in which a user designs a stencil image using a combination of strokes, primarily employing brush and fill tools. Each time a stroke is completed, the system automatically generates a stencil image in which the islands are connected to the template.

Jain and others studied the creation of multiple overlaid stencils that can be used to create multicolor images, rather than simple stencils [7]. Multilayer stencils allow artists to create images of more complex designs, although the proposed creation is much more complex than a single-layer stencil, specifically during image segmentation and bridge selection. The authors also carry out Markov Random Field-based k-color image segmentation. Then, layer ordering is performed to determine the coloring order, which is not used during the creation of a monolayer layer. Finally, the islands are connected in each layer.

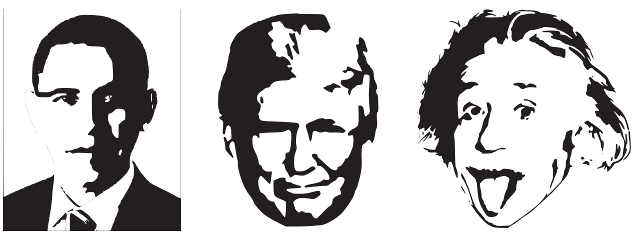

FIGURE 2 Facial stenciled images (reprinted from openclipart.org, Creative Commons Zero 1.0 Public Domain License)

Relief is a sculptural technique in which shapes are carved such that they extrude from the background, as shown in Figure 3. As an artistic medium, a relief spans the continuum between 2D drawings/paintings and a full 3D sculpture. Along this spectrum, alto-relievo (high relief) is closer to full 3D whereas flatter works are described as basso-relievo (low relief or bas-relief).

There have been many studies on the generation of reliefs from 3D models or 2D images [8–12]. By using a 3D model, camera, and few parameters describing the relative attenuation of different frequencies in a shape, Weirich et al created a relief that gives the illusion of a 3D shape from a given vantage point while conforming to a greatly compressed height [8].

By using an input image and the corresponding light directions, Alexa and Matusik proposed a method for obtaining a relief such that its diffuse shading approximates the input image when illuminated by directional lighting [9]. They defined a discrete model for the area in the relief surface that corresponds to a pixel in the desired image. This model introduces the necessary degrees of freedom to overcome the theoretical limitations in the shape resulting from shading and practical requirements such as the stability of the image under changes in viewing conditions and limited overall variation in depth.

Sykora and others presented a new approach to generate global illumination renderings of hand-drawn characters by using a small set of simple annotations [10]. They formulated an optimization process that automatically constructs an approximate geometry that is sufficient to evoke the impression of a consistent 3D shape.

FIGURE 3 Persian mid-relief from the Qajar era (reprinted from Zereshk, Qajar relief in Tang-e Savashi, https://commons.wikimedia.org/wiki/File:Qajari_relief.jpg, CC BY-SA 3.0)

To and Sohn proposed a new method for generating a bas-relief from a monocular image of a human face [11]. They built a feature map called face parts map region to locate the position and area of each facial feature, adjusted the brightness values of the facial areas, and finally elevated the resulting surface based on pixel intensities.

Lee and Sohn proposed a new approach to generate a cartoon-style bas-relief surface based on non-photorealistic rendering techniques [12]. They used coherent line drawing and histogram-based quantization methods to convert the depth map into several depth layers and generated the resulting cartoon-style bas-relief from these layers.

A lithophane is an etched or molded artwork composed of thin translucent porcelain that can only be seen clearly when back lit with a light source [13]. The concept of lithophanes has recently been explored through additive fabrication [14], which generates a thin bas-relief 3D model from a photo as in [11,12] and prints the model by means of a monochrome 3D printer. One of the advantages of a lithophane printed from a monochrome 3D printer is that it appears in gray tones when back lit despite being of a single color. However, it requires illumination.

3 | STENCIL-BASED 3D FACIAL RELIEF MAKING SYSTEM

The system proposed in this paper performs several steps to create a stencil-based 3D facial relief as shown in Figure 4. First, the system obtains a 2D facial image and a 3D facial model of a customer using Kinect. The image and model are used as raw sources for generating a stencil image and the relief information. Then, the system performs segmentation of the facial image, which consists of image adjustment and image segmentation. The resulting image is used as an initial stencil image. After this, a complete stencil is created by merging the islands and determining the boundary shape. The 3D relief form is constructed by extruding the stencil image by using the facial polygonal mesh data obtained in the first step. Finally, the 3D facial model is printed.

3.1 | Facial image and model acquisition

The first step in creating the proposed relief is acquiring a customer's facial image and the corresponding 3D model. First, a color image and a depth image of the customer's face are obtained using one shot from an inexpensive 3D depth capturing device such as Kinect. Because the field of view of Kinect is wide, the area occupied by the face in the color image is relatively small. Thus, it is inadequate to use the color image as is in the following step of the stencil image creation. Therefore, it is necessary to only extract the face region separately from the color image, as shown in Figure 5A. The Kinect face API is used to extract the facial region from the entire image.

It is also necessary to obtain the facial area at the pixel level to generate a 3D model of the face. A grabcut [15] is applied to the facial image based on skin color to create a mask for the facial area. Second, a 2D Delaunay triangulation is applied on the pixels of the mask to generate a planar polygonal mesh. The final 3D polygonal mesh is obtained by applying the depth of each corresponding pixel of the image to the z value of each vertex of the planar polygonal mesh. The 3D polygonal mesh is spiky because the depth image values obtained from Kinect can be inaccurate and spiky. Because of the noise present in the mesh, a smoothing filter is applied.

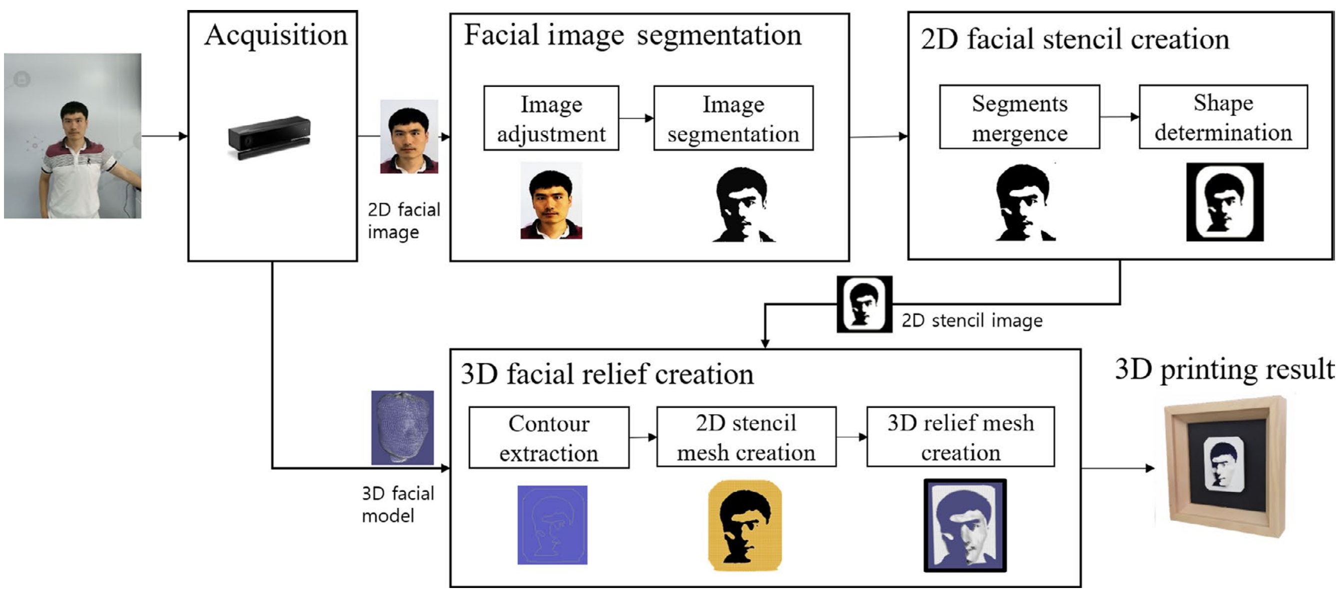

FIGURE 4 Block diagram of proposed system for creating a stencil based 3D facial relief

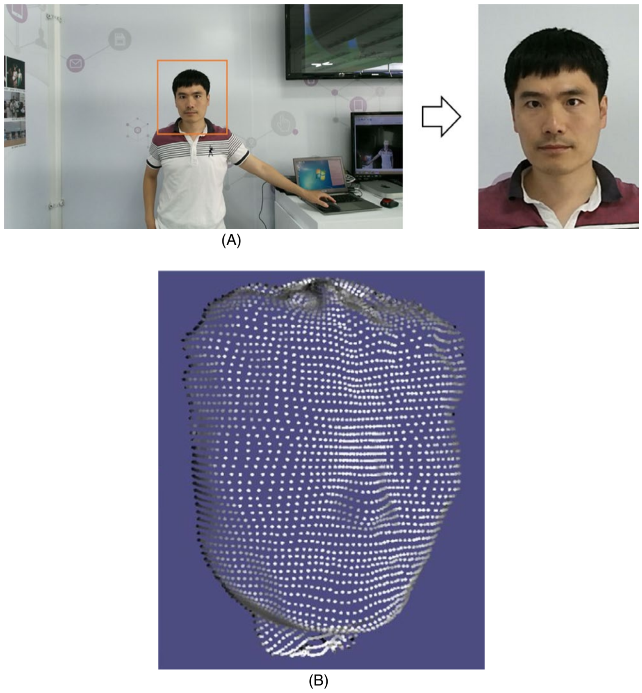

FIGURE 5 Face image and 3D face model captured using Kinect: (A) The facial region in the color image can be obtained by the Kinect face API, and (B) the 3D facial model is created by utilizing the facial region and the depth map

Figure 5B shows the 3D face model of a customer created through this process.

3.2 | Facial image segmentation

With a stencil, only one color of paint is usually applied to create a particular work. For multilayer stencils, only the number of colors equal to the number of layers is used. Therefore, it is necessary to reduce an original facial image composed of millions of colors into an image composed of a few colors. The *K*-means clustering algorithm, which is widely used in non-photorealistic rendering problems, is also used in image segmentation [5,7].

Image segmentation is very important in terms of determining the shape of the stencil and the shape of the entire work. If the stencil contours are too close or too rough, they are not suitable for 3D printing. To achieve good image segmentation when creating a stencil, moderately large, properly scattered islands and smooth boundaries should be used. The Euclidean distance between two colors in an RGB color space is known to be an inappropriate approach [16] and, therefore, a preprocessing technique was applied before conducting the *K*-means clustering.

First, a bilateral filter was applied to preserve the edges of an image and remove its noise. A bilateral filter uses a nonlinear combination of nearby image values to smooth the images while preserving the edges [17]. The filter replaces the intensity of each pixel with a weighted average of the intensity values from nearby pixels. The weights depend not only on the Euclidean distance between pixels but also on the radiometric differences [17].

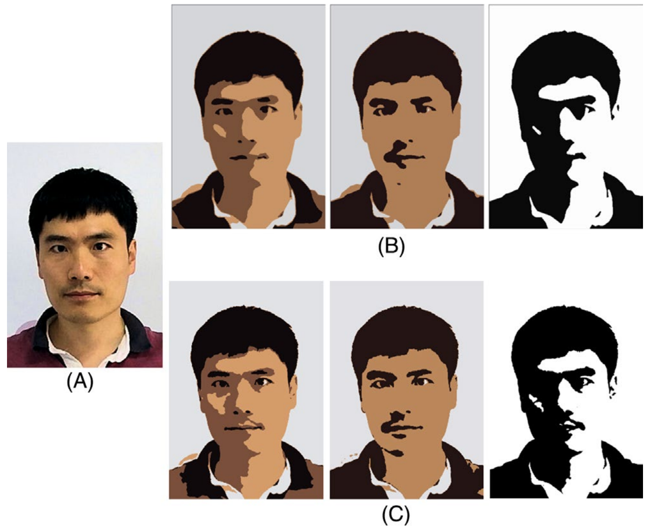

FIGURE 6 Results of image segmentation according to *k* values in the respective color spaces (A) 24-bit color image; (B) The results of the image segmentation for four, three, and two color groups in a CIE LAB color space; (C) Those in an RGB color space

Second, the color space of the image was converted from RGB into CIE LAB because it is known that a CIE LAB color space has better quantization results than an RGB color space [16]. Figure 6 shows the results of the *K*-means clustering algorithm for four, three, and two color groups in the respective color spaces after the bilateral filter is applied to a facial image. The results of the image segmentation in a CIE LAB color space have more smooth edges and fewer islands than those in an RGB color space, showing that the image segmentation in a CIE LAB color space is more suitable for 3D printing.

In the proposed system, the final 3D model should be made with only one color to utilize a monochrome 3D printer. The facial image is converted to a binary image because only a specific area of the facial image can be printed. The remaining area is discarded. Thus, the *K*-means clustering algorithm with $k = 2$ is applied to generate a binary stencil image. The state of the original image has the greatest effect on the result of the *K*-means clustering algorithm. The result is drastically changed by adjusting the brightness and contrast of the image, although the direction of light in the scene of the image is fixed. The proposed system allows a user to adjust the brightness and contrast of the acquired facial images to obtain a binary image that properly represents facial characteristics.

FIGURE 7 Various binary images owing to changes in brightness and contrast

Figure 7 shows the results of the K-means clustering algorithm with $k = 2$ obtained by varying the brightness and contrast.

Figure 8 shows a facial image with tuned brightness and contrast, and the resulting binary image. The binary image is regarded as an initial stencil image. The white portion of the binary image corresponds to the stencil template, and the dark portion corresponds to the cut-out holes that are not printed.

3.3 | Creation of stencil image

The initial stencil image from the previous step is incomplete. As mentioned earlier, for a stencil to be reusable, the stencil template must be a single connected plate. White regions are generally separate in the initial stencil image generated using the *K*-means clustering algorithm. As seen in the right of Figure 8, several small white areas are separated from each other and must be connected.

To identify the islands, the Suzuki's method [18] is used to find the contour of each white area in the image. Figure 9 shows the contours of the islands in the initial stencil image. There are three such islands in this picture.

Next, to stabilize the structure of the 2D stencil image, all of the islands are linked together into a single piece. Before linking, the overly small islands are removed to simplify the shape of the contours. They are indicated by the blue circle in Figure 10. Low-cost 3D printers do not have the precision necessary to properly print the overly small islands.

FIGURE 8 Tuned facial image and resulting binary image

FIGURE 9 Contours of the islands in the initial stencil image

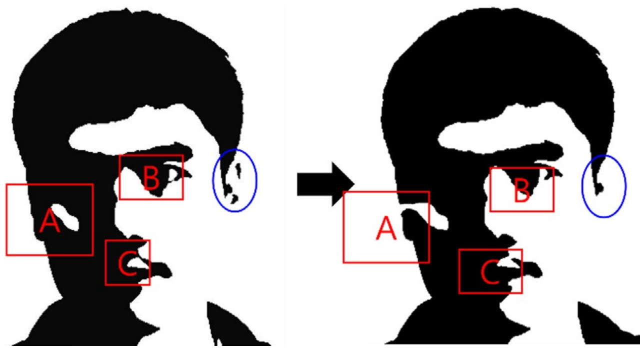

FIGURE 10 Merging bright segments into a single connected object

Figure 10 shows that labels A, B, and C are assigned to each identified island. Similar to Bronson et al, we constructed a fully connected graph that considers islands as nodes [5]. The distance between two islands i and j is as follows:

$$d_{ij} = \min_{(x_i,y_i)\in C_i,(x_j,y_j)\in C_j} \sqrt{(x_i-x_j)^2+(y_i-y_j)^2}$$

where (x, y) is the coordinate of a pixel in the contour of the corresponding island, which represents the closest distance between the pixels forming the contours of the islands. The minimum spanning tree is then built from the graph. The edges in the tree are the bridges that should be placed between islands. A bridge is placed between two islands i and j by drawing a line from p_i to p_j with a specified width, where p_i and p_j are the pixels whose distance is d_{ij}.

Figure 10 shows a stencil image before and after the bridges are placed.

The border of the current stencil image is decorated to achieve an aesthetic effect. The border of the previous stencil image is always rectangular and appears plain. The proposed system allows the user to select the boundary shape in consideration of the central facial shape and desired style. In the proposed system, several boundary shapes such as a circle, an ellipse, and a rounded rectangle are prepared in advance. When the user selects a specific boundary shape, it is applied to the current stencil image to complete the final stencil. Figure 11 shows stencils with a circular boundary and a rounded rectangular boundary.

3.4 | Construction of a 3D facial relief model

A typical stencil technique uses a laser cutter to cut a thin sheet of cardboard, plastic, or metal based on the created stencil image to create a physical stencil template.

In this paper, the results are produced in 3D form rather than on a thin 2D sheet. Unlike common types of reliefs, the proposed relief has holes in it. The following procedure is conducted to create a 3D facial relief model.

First, the contours are extracted again to find the stencil template part in the stencil image. Figure 12 shows the contours corresponding to the stencil image in Figure 11.

FIGURE 11 Stencil images with a circular boundary shape and a rounded rectangular shape

FIGURE 12 Contours extracted from the stencil image

Second, based on the extracted contour information, a planar polygonal mesh is created corresponding to the stencil template part. For this step, the vertices that correspond to each pixel of the stencil template are created in the stencil image. A quad face is then constructed by connecting neighboring vertices for each vertex and triangulated to complete the planar polygonal mesh. The z values of the vertices of the planar polygonal mesh are set to zero. Figure 13 shows a planar polygonal mesh created in this manner.

Third, a final 3D facial relief model is formed by applying an extrusion operation on the planar polygonal mesh such that the coordinates of the newly duplicated vertices are set as follows:

$$x_{v_{\text{new}}} = x_v,$$

$$y_{v_{\text{new}}} = y_v,$$

$$z_{v_{\text{new}}} = \begin{cases} t + z_{v_{\text{face}}} & \text{if } v \text{ corresponds to } v_{\text{face}} \text{ in the face region,} \\ t & \text{otherwise,} \end{cases}$$

where t is a user-specified thickness. To satisfy various customer requirements, it is necessary to ensure that the resulting extruded 3D models can perform flexible transformation operations. Figure 14 shows a parameter adjustment and preview widget for

FIGURE 13 Planar polygonal mesh created from the stencil image

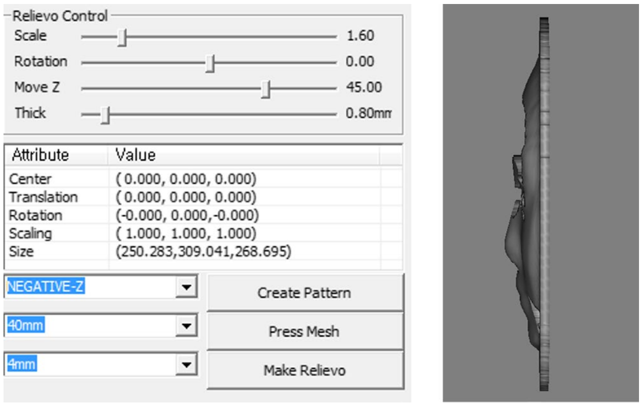

FIGURE 14 Parameter adjustment and a preview widget for several transformation operations

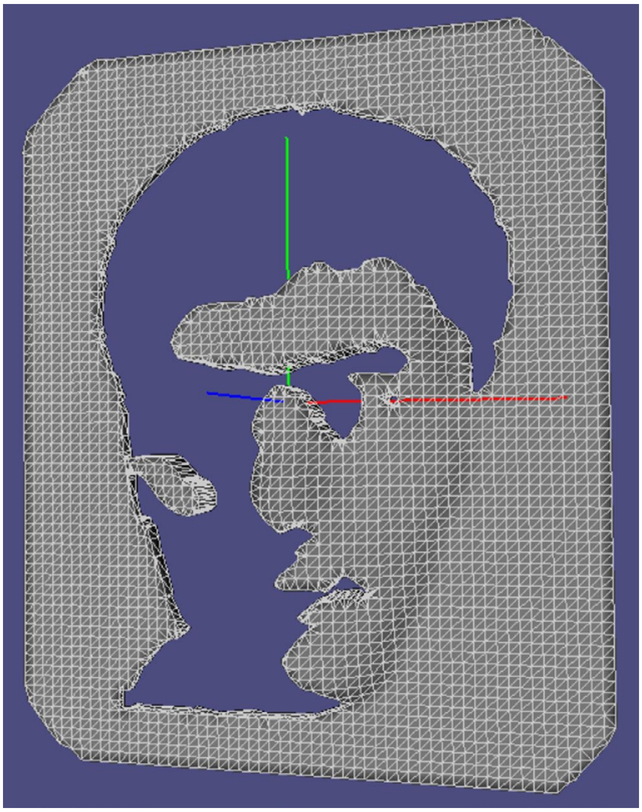

FIGURE 15 Final water-tight facial relief model

several transformation operations, including geometric transformation like translation, rotation, and scaling. Figure 15 shows the final 3D facial relief model. Because the final relief model is water-tight, the model can be printed using a 3D printer.

4 | EXPERIMENTAL RESULTS

The proposed system was implemented on a standard PC with an Intel 3.6 GHz i7 CPU and Kinect v2.

OpenCV software was used for image processing. The Kinect capture environment does not have any special requirements, but it is necessary to provide a side light to obtain a good facial image on the stencil.

The time taken to capture a facial image from Kinect and create a final stencil-based 3D facial relief model is approximately 2 minutes. Because the proposed system does not conduct CPU-intensive jobs, it consumes little time during most steps, with the exception of interactive operations.

Figure 16 shows the output of the final 3D facial relief model printed by a low-cost monochrome 3D printer at different angles. Its size was approximately $4.5 \times 6.0 \times 1.5\ \text{cm}^3$, and much of it was comprised of empty space. Therefore, the actual output time taken was only about 10 minutes despite the slow output speed of 3D printing.

Like a normal stencil, the work has several holes through which the background surface, a dark blue semi-transparent acrylic plate, is visible. Although the work itself was made by laminating a white material, its overall image appears to represent the human face using two colors. Because the work is curved in 3D, it does not appear flat; it is stereoscopic.

Generic 2D stenciled images, as shown in Figure 2, represent human faces well, but they look flat and non-realistic. Compared to these 2D stenciled images, the proposed product appears more realistic.

Figure 17 shows two types of 3D outputs printed by a monochrome 3D printer. The 3D model of the simple

FIGURE 16 Final stencil-based 3D facial relief using a monochrome 3D printer

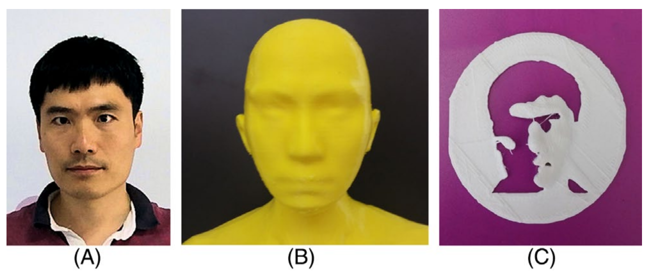

FIGURE 17 Comparison between a simple 3D selfie printed by a monochrome 3D printer and the stencil-based 3D facial relief proposed in this paper

selfie was generated by 3D scanner based on the stereo cameras and adapted to a standard bust model. The selfie is entirely 3D, but because it is expressed in a single color, it appears flat. Figure 17C shows the result of the proposed system. The 3D face model used in the proposed system has relatively low quality as the resolution of the depth image captured from Kinect is 512 × 424 and only the facial area is reconstructed. Nevertheless, the proposed 3D facial relief seems to be represented in two different colors, such as stenciled pictures, and it provides a stereoscopic feeling due to its 3D nature. As a result, it looks more natural than the selfie and better expresses facial features.

Figure 18 shows a stencil-based 3D facial relief with a wooden frame. The framed relief represents the two-tone result of the stencil and relief technique, demonstrating an unmistakable resemblance to the real face compared to similar techniques. In other words, the proposed system shows that, despite the use of a cheap scanner, such as Kinect, and an inexpensive monochrome 3D printer, it is possible to create valuable artistic works by combining existing stencil and relief techniques.

The 15-minute period required from the capturing of the face, using Kinect, to the output of the piece shows that the system proposed in this paper can produce customized on-the-spot gifts for customers at an exhibition venue. Figure 19 shows an example of the project, completed during this study, applied to customers at an international exhibition related to 3D printing. Figure 19A shows several samples obtained by using an FDM printer and Figure 19B shows several samples obtained by using a DLP printer.

FIGURE 18 Stencil-based 3D facial relief with wooden frame

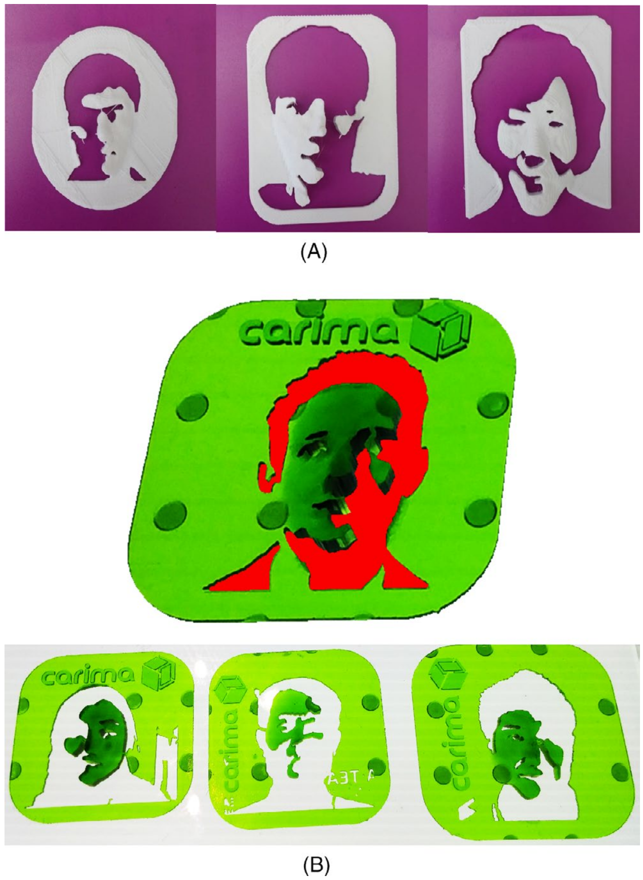

FIGURE 19 Stencil-based 3D facial reliefs printed on the spot

5 | CONCLUSIONS

This paper proposes a new stencil-based 3D facial relief creation system using a low-cost scanner and 3D printer. While the proposed system has the advantage of low cost, it does have drawbacks, namely producing only single color works with an inaccurate 3D geometry. To overcome these limitations, the proposed system uses stencil and relief techniques. It creates a binary stencil image by partitioning the pixels of the human facial image acquired from a low-cost scanner into two regions based on certain criteria. A 3D facial relief model is then completed based on a 2D stencil image by assigning the heights of the bright portion of the image and making the model water-tight. Experimental results reveal that a piece produced using the proposed system has the two-tone quality of a stencil and the 3D characteristics of a relief.

The system was also demonstrated to be capable of creating reliefs within a short period of time, unlike existing 3D selfie services. The proposed system is expected to enable new types of competitive 3D printing services by creating new products of good quality, similar to those of existing 3D printing services, but with lower cost hardware and within a shorter period of time.

The main limitation of the proposed system is that the lighting environment has a great effect on the quality of the facial image segmentation. The required side lighting must be consistent and bright to obtain a good facial image with balanced contrast. Easier and more flexible solutions are left for future work.

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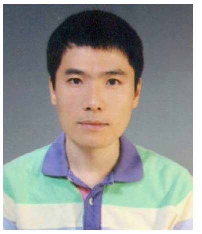

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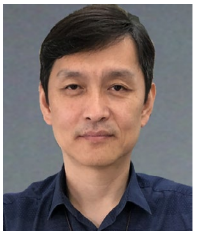

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