3D Surface Reconstruction Method using a Coded Binary Pattern

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Abstract. Coded structured light is a widely used technique for three-dimensional (3D) reconstruction. It creates artificial features on the surfaces of objects and then acquires images from one or more points of view. The pattern in the images is decoded to locate correspondence. The 3D information can be reconstructed by triangulating the correspondences between the projected and decoded patterns. In this paper, a method to reconstruct 3D information using structured light is proposed. The pattern is represented using a binary pattern and it is coded for uniqueness in the search range. The coded pattern is projected using an infrared laser and a diffraction optical element (DOE) for the invisible areas. Then, the pattern in the image captured using a sensitive camera is matched with the projected pattern. As a result, the disparity between matched points draws a 3D reconstruction.

Keywords: 3D reconstruction, coded structured light, binary coded pattern

1 Introduction

Three-dimensional (3D) reconstruction is an important topic in computer vision because it is used in numerous applications such as remote sensing, object recognition, industrial inspection, and robot systems, among others. Generally, 3D reconstruction methods are categorized into passive and active techniques. In passive techniques, the scene is imaged using camera from two or more points of view and then the correspondence between the images is found. Then, the correspondence is triangulated and the 3D position is obtained. However, it is difficult to find correspondence between images from different cameras, even when considering the epipolar constraints. Therefore, the passive techniques are limited in textureless scenes due to the problem of finding correspondence [1]. In contrast, active techniques replace one of the two cameras with a device that projects a pattern onto the object surface and the scene is captured using one or more cameras. The projected patterns create an artificial feature on the object’s surface that can be used as correspondence, particularly in textureless scenes. Then, 3D reconstruction is possible when looking for differences between the projected patterns and imaged patterns. This is similar to passive techniques [3].

The structured light scheme differs according to the type of pattern and projection method such as time division pattern projection, coded color patterns, and coded
patterns. The time division pattern is reliable and accurate for dense 3D reconstruction, but it cannot be used for real time or moving target 3D reconstruction. In coded color patterns, the 3D reconstruction results are affected by the object and background colors. Coded patterns can reconstruct 3D surfaces for moving targets and independent colors, but it requires a decoding step for pattern recognition to match the projected pattern.

In this paper, a coded structured light method is proposed for 3D reconstruction. The pattern is coded for binary representation and projected using an infrared laser and a diffraction optical element (DOE) for the invisible areas. The invisible pattern in the scene is imaged using a sensitive camera. Then, after pattern recognition, the patterns from the projected pattern and the recognized pattern are matched in order to reconstruct the 3D surface. The following section introduces the pattern coding strategy. The pattern detection and matching method for recognition is also presented in Section 2. Then, the results with the disparity of correspondence are presented in Section 3, and the paper is concluded in Section 4.

2 3D Reconstruction Method

The type of pattern affects the structured light performance including the resolution, speed, and accuracy. Time multiplexing has an advantage in dense 3D reconstruction; however, it cannot reconstruct moving targets [4]. Coded color patterns have a disadvantage if the target has a similar color to the colored pattern. If the pattern consists of a specific shape, then it may also be affected by the objects and background color. However, coded patterns can reconstruct a moving target in 3D; even if it is represented using binary symbols, it is independent of the color, shape, and other details from the background and objects. Coded patterns have a disadvantage in pattern decoding. Therefore, pattern coding methods, such as the pseudorandom, M-array, perfect map, and De Bruijn methods, have been investigated for a long time in order to facilitate the pattern decoding. These pattern encoding methods create symbols for uniqueness within a specific range. The projected pattern is compared with the imaged pattern for recognition. If the pattern is repeated within the search range, matching errors occur. Despite these methods, the light source remains visible and it is difficult to subtract the pattern from the image [2].

This research used a coded binary pattern that was projected using an infrared laser and DOE. There was a small object shape and the pattern is clearly represented. The infrared source was also affected by the quality of the material, but it was not visible. Figure 1 presents the image captured using the sensitive camera in infrared light. Clear patterns and shadows can be seen in the image. The background effect is eliminated and the object is recognized using the shape of the shadow. There is also a material effect: because the material of the cylindrical object has a lower level of light reflection, the projected pattern is faint and, in some areas, invisible. In this case, the pattern does not appear despite the visible light.

In order to reconstruct the 3D image, the surface is triangulated using the difference between the projected pattern and the imaged pattern. The difference is represented using the shift of correspondence points on the epipolar constraints. In this research, the correspondence points are dots that have symbols. The symbols consist of white dots and black dots. The white dots are recognized easily, but it is difficult to
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distinguish them from the background. Therefore, the black dot recognition uses the results of the white symbols.

Fig. 1. Image captured using a sensitive camera with a coded pattern that was projected using an infrared laser and DOE.

In order to match the white dots, a sliding window method was used because the symbols are unique in the search. The pattern is designed to maintain the uniqueness of the symbols with a specific size in the search range. The size of the sliding window is the same as that of the symbol. The five steps for matching the symbols are as follows.

1. A symbol is extracted from the pattern in the image to the window.
2. The symbol in the projected pattern is extracted to the window.
3. The matching cost between the windows is calculated.
4. The window slides along the search range in the projected pattern and Steps 2 and 3 are repeated until the symbol that has the maximum matching cost is found.
5. A white dot in the center of the window is matched to the one in the window that has the maximum matching cost.

The matching cost between the windows is calculated when the proportion of the correct position of the white and black dots is more than an arbitrary threshold value. If the proportion is less than the threshold value, the symbol is regarded as a different symbol to the one being sought. In contrast, the matching cost is the proportion of dividing the number of correction positions of white dots by the number of white dots in the window.

After the white dots are matched, the black dots are matched using the positions of the matched white dots. The black dots are matched along the projected pattern. In this case, a symbol is first extracted from the projected pattern to the window where the black dot is centered. According to the position of the matched white dots, the position of the black dot in the image is decided. Finally, the disparity between the matched symbols reconstructs a 3D surface.
3 Results

The following results demonstrate a disparity image using the sliding matching method with a coded pattern. The experimental environments were as follows. The positions of the projector and camera were collinear. The projected pattern and scene that are captured using the camera are horizontal. The object position was 1.5 m from the camera and projector. The illumination conditions were an indoor environment and a projector infrared laser source. A geometrical figure and a bust sculpture were used in the experiments.

![Image](image_url)

**Fig. 2.** (a) Input image captured using a sensitive camera for the geometrical figure (Fig. 1). (b) Result of the disparity between the matched projected pattern and the pattern in (a). (c) Input image captured using a sensitive camera for the bust sculpture. (d) Result of the disparity between the matched projected pattern and the pattern in (c).

Figure 2 presents the disparity images that illustrate the difference between the symbols in the projected pattern and the symbols recognized in the imaged pattern. The 3D reconstruction is drawn through applying real distance to the disparity. Despite the holes and shadows due to mismatching and false detection, the quality of disparity image is acceptable. The shadowed areas are based on the projector illumination and the quality of material. In Fig. 2(a), the symbol on the object under the geometrical figure is not recognized; furthermore, symbols are not present in the
left side of the bust sculpture in Fig. 2(c). The quantity of dots in the disparity image is described in Table 1.

<table>
<thead>
<tr>
<th>Scene</th>
<th>Projected dots</th>
<th>Projected white dots</th>
<th>Matched dots</th>
<th>Detected white dots</th>
<th>Matched white dots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical figure</td>
<td>34,815</td>
<td>3860</td>
<td>28,116</td>
<td>3204</td>
<td>2907</td>
</tr>
<tr>
<td>Bust sculpture</td>
<td>34,815</td>
<td>3860</td>
<td>24,586</td>
<td>3086</td>
<td>2688</td>
</tr>
</tbody>
</table>

Table 1 presents the total number of projected dots and matched dots. The matching proportion is approximately 80.75% and 70.61% despite the holes and shadow effects. For the detected white dots, the performance increased to approximately 90% and 87%. As a result, most recognized symbols were matched with the projected symbols.

4 Conclusion

The proposed coded structured light method projects a pattern onto an object in order to reconstruct its 3D surface. Unlike passive methods, the coded structured light creates an artificial texture that can be used to reconstruct the 3D surface. The coded structured light can also reconstruct a 3D surface for moving targets. In infrared conditions, the color of the object and background do not affect the pattern recognition. This paper proposed a method for 3D reconstruction using coded structured light in infrared conditions. A scene is captured using a sensitive camera, and the pattern in the image is recognized. In order to determine the difference between the projected pattern and the imaged pattern, a sliding window that is the same size as the pattern symbol was used. First, the white dots were matched, and then the black symbols were matched using the matching information from the white dots. Finally, the difference was calculated using the position of the matched dots. This paper illustrated the disparity images from the results of the matching performance. Despite the holes and shadows where the white dots were not visible, the total matching performance was more than 70% and the white dot matching performance was more than 87% for verification in the visible areas. This paper demonstrates the possibility of reconstructing the 3D surface using coded structured light in infrared conditions.

Acknowledgments. This work was supported by the DGIST R&D Program of the Ministry of Education, Science and Technology of Korea (grant no. 13-NB-05).
References