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Realtime Structured Light Vision with the Principle of Unique Color Codes

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***Abstract*—To date, several successful structured light vision systems for accurate 3D measurement in machine vision have been set up. However, these are usually limited to scanning stationary objects or static environments since tens of images have to be captured for recovering one 3D scene, which results in the industry largely avoiding this technology. This paper presents a method of grid-pattern design based on the principles of uniquely color-encoded structured light, to improve the reconstruction efficiency for real-time processing. For a live scene, the 3D measurement is desired to only capture a single image. To realize this, an important problem for the color- encoded projection is the unique indexing of the color codes in the image. It is essential that each light grid be uniquely identified by incorporating the local neighborhoods in the pattern so that 3D reconstruction can be performed with only local analysis of a single image. This paper describes such a method in the design of the special grid patterns and its corresponding 3D reconstruction method for fast vision perception.**

I. INTRODUCTION

In the computer vision community, many three-dimensional (3D) reconstruction methods have been explored by researchers in the past years for obtaining the 3D model of an object. However, fast (especially real-time) reconstruction of a 3D object surface from images is still a very challenging problem in this field [1]. The most widely known passive method for 3D acquisition is stereovision. One difficulty is the correspondence problem. To avoid it, we can consider the alternative active method, i.e. the structured light system in cooperation with a light coding method. One of the structured light systems uses a single-line stripe. The advantage of this approach is that it greatly simplifies the matching problem, whereas the drawback of this approach is that only one single stripe of 3D data points can be obtained with each image shot. To speed up the data acquisition process, multiple-line stripe patterns are used instead. Osawa *et al* [3] used pattern of four gray levels with a space-time scanning method. Various gray code patterns are projected onto the object in time series when taking images with a camera. The advantage of this approach is that it speeds up the acquisition process and still simplifies the matching problem. However, it still needs several image shots to generate a time series code of lighting. In order to reduce the number of input images, a color-stripe pattern is generated, and several cameras are used to take images from various viewpoints. Chen *et al* [4] combined color-structured light and stereo vision by using an uncalibrated structured light source to project a pattern of color stripes. Zhang *et al* [5] used only one camera for capturing an image of a projected stripe pattern, and then matched the observed edges in the image. The correspondence problem is solved using a multi-pass dynamic programming algorithm.

The early structured light systems using a gray-coding method have the advantage that a much smaller number of images is required, but they still need about ten images of the scene for recovering one 3D image. As a result, they can only be used to reconstruct stationary objects. It is not possible to capture more than one image of the same part of an object for perceiving the 3D information of moving or non-rigid objects. In such cases, 3D measurement using a single image is desired. For this reason, an alternative method is required, which uses a color projector that can be controlled by a computer to generate arbitrary desired color patterns. Different from the case of the stripe light vision system, where the coordinates on the projector can be determined by analyzing the bit-plane stack obtained from multiple images, the coordinates in the color projection vision system have to be determined in a single image.

A problem of the color-encoded projection is the unique indexing of the light codes in the image. If all light rays are visible in the image and if each light grid is completely visible then indexing is trivial. However, in many cases some light grids are invisible or only partially visible due to occlusions and discontinuities of the objects. Therefore it is essential that each light grid be uniquely identified by incorporating the local neighborhoods in the light pattern. This paper presents an idea to design the grid patterns for light projection and fast code matching. Based on this, the triangulation for computing the 3D coordinates of object points simply involves calculating linear equations combined from the 2D coordinate data from the image and indexed color codes as there is no correspondence problem.

II. COLOR-CODING AND VISION SYSTEM

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A. Structured Light Vision System

The structured light system considered in this paper consists of a CCD camera and a digital projector (Fig. 1). That is similar with the traditional stereo vision system, but its second camera is replaced by the light source, which projects a known light pattern on the measuring scene. Another single camera captures the illuminated scene. The required 3D information can be obtained by analyzing the deformation of the imaged pattern with respect to the projected one. Of course, some correspondences between the projected pattern and the imaged one should be solved. And the correspondence problem can be directly solved by codifying the projected pattern, so each projected light point carries some information. When the point is imaged on an image plane, this information can be used to determine its coordinates on the projected pattern.

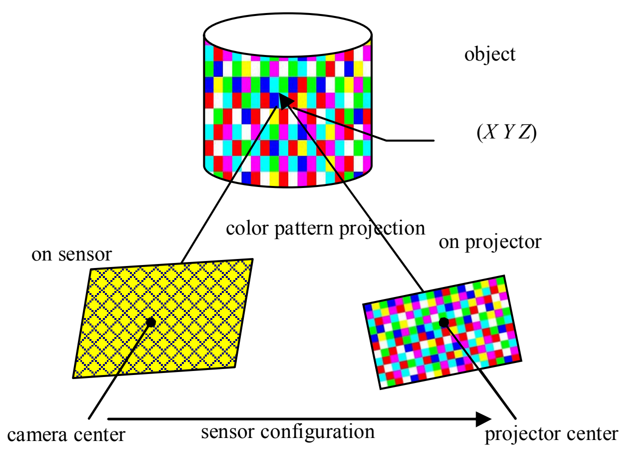

Figure 1. Sensor structure for color-coded vision

For such a vision system, the input is 2D-projections of 3D world objects and the vision task is to reconstruct the objective world according to the two-dimensional projection images on the camera and the projector. The camera can be modeled with a PTM (perspective transformation matrix). Similarly, the projector can also be modeled by a PTM for the transformation from world points to the projector's optical device. These two PTMs are combined similarly in a triangulation equation to generate the conversion from image coordinates to 3D world coordinates. Details about the surface measurement principle for obtaining the 3D information from triangulation may be found in previous contributions [6]-[8]. The formulated equations have been adapted to the projection of an image and the capture of another, and as can be seen, there is not much difference to the triangulation used in a stereoscopic system.

B. Existing Coding Methods

In a coded structured light system, the patterns are specially designed so that codewords are assigned to a set of pixels. Batlle *et al* [2] have extensively reviewed the pattern projection techniques developed in the last decade and classified the coding strategies as time-multiplexing, neighborhood codification and direct codification. The time-multiplexing method generates the codewords by projecting a sequence of patterns along time, so the structure of every pattern can be very simple. In spite of increasing the pattern complexity, neighborhood codification represents the codewords in a unique pattern. And direct codification techniques define a codeword for every pixel, which is equal to its grey level or color.

For time-multiplexing techniques, one of the most commonly exploited strategies is based on temporal coding [16] which can achieve high accuracy in the measurements. The advantages of these techniques are the easy implementation, the high spatial resolution and the accurate 3D measurements that can be achieved. The main drawback is their inapplicability to moving surfaces since multiple patterns must be projected. Techniques based on projecting stripe patterns encoded with gray code can obtain very good accuracy, but not maximum resolution. In order to obtain maximum resolution, a technique based on the combination of gray code and phase shifting must be used [9]. Its drawback is the large number of projecting patterns (more than 24 images). If maximum spatial resolution is not the principal aim of the application, but rather the minimization of the number of projecting patterns, a technique based on n-ary code is appropriate. Such methods obtain an accuracy result equal to or even better than a gray code approach, reducing exponentially the number of projecting patterns. However the system using n-ary codes must be calibrated in order to correctly differentiate among the set of grey levels or colors used.

For direct coding techniques, it creates a pattern so that every pixel can be labeled by the information represented on it. Thus the entire codeword for a given point is contained in a unique pixel. The recent works in the community by Griffin *et al* [10] and Salvi *et al* [18] brought us useful contributions to this technique. In order to achieve a unique result it is necessary to use either a large range of color values or introduce periodicity. This will result in a high resolution of 3D information, in theory. But the sensitivity to noise is very high because the distance between codewords is nearly zero. Furthermore the imaged colors depend not only on the projected color but also on the intrinsic color of the measuring surface. This means that one or more reference images should be taken. Therefore these techniques are not suitable for dynamic scenes.

The spatial neighborhood coding is another important method in structured light systems. This method tends to concentrate all the coding schemes in a unique pattern. However, the decoding stage becomes more difficult since the spatial neighborhood cannot be recovered and 3D errors can arise. The advantage of spatial neighborhood techniques over time-multiplexing is that this strategy permits measuring of moving surfaces. However, since the codification must be condensed in a unique pattern, the spatial resolution is lower. Moreover, local smoothness of the measuring surface is assumed in order to correctly decode the pixel neighborhoods.

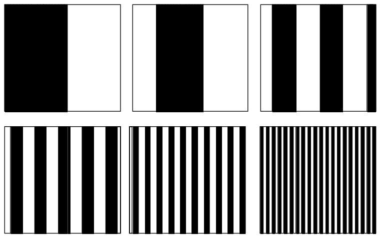

Figure 2. A typical gray-coding method [16] (1984)

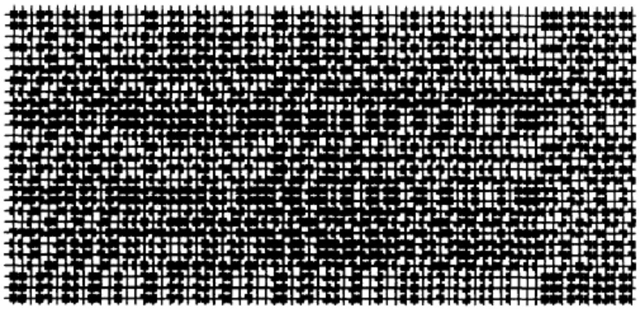

Figure 3. The pattern designed by Griffin *et al* [10] (1992)

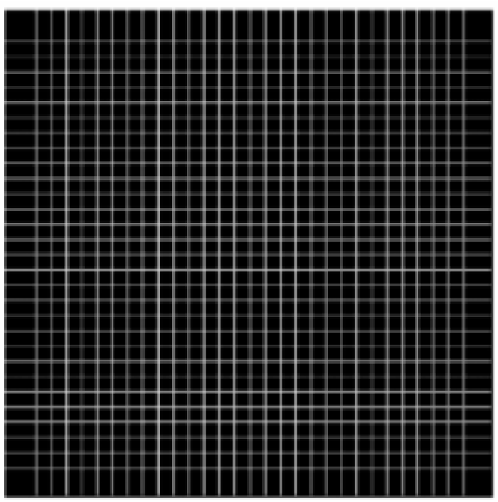

Figure 4. The pattern designed by Salvi *et al* [18] (2004)

C. Grid-Pattern Coding Requirements

In an effort to avoid the drawbacks of the above-mentioned coding techniques, many researchers have tried to improve the projected light pattern. Griffin *et al* [10], in 1992, have carried out a mathematical study about what should be the largest size allowed for a coded matrix of dot patterns.

Different from the case of the stripe light vision system where the coordinates on the projector can be determined by analyzing the bit-plane stack obtained from multiple images, the coordinates in the color projection vision system have to be determined in a single image. A problem of the color encoded projection is the unique indexing of the light codes in the image. If all light rays were visible in the image and if each light grid were completely visible then indexing would be trivial. However, in many cases some light grids are invisible or only partially visible due to occlusions and discontinuities of the objects. Therefore it is essential that each light grid be uniquely identified by incorporating the local neighborhoods in the light pattern.

This paper presents a method for designing grid patterns that can meet the practical requirements. Let *P* be a set of color primitives, $P = \{1, 2, \cdots, p\}$. These color primitives are assigned to an $m \times n$ matrix M to form the encoded pattern which may be projected onto the scene. We define a word from M by the color value at location (*i, j*) in M and the color values of its 4 adjacent neighbors. If x_{ij} is the assigned color point at row *i* and column *j* in M, then the word for defining this location, w_{ij}, is the sequence $\{x_{ij}, x_{i,j-1}, x_{i-1,j}, x_{i,j+1}, x_{i+1,j}\}$ where $i \in \{1, 2, \cdots, m\}$ and $j \in \{1, 2, \cdots, n\}$ (Fig. 5), i.e. w_{ij} is a substring as following

$$w_{ij} = (x_{ij},\ x_{i,j-1},\ x_{i-1,j},\ x_{i,j+1},\ x_{i+1,j}) \tag{1}$$

1	2	1	2	1	2	1	2
2	1	2	1	2	1	2	1
1	2	4	3	1	4	3	2
2	1	3	1	2	3	1	4
1	3	1	4	3	1	3	2
2	4	2	1	2	3	1	3
1	2	1	4	1	4	2	4

Figure 5. A unique word (13324) in the pattern matrix

If a lookup table is maintained for all of the word values in M, then each word defines a location in M. Then we can know that an $m \times n$ matrix M has $(m-1)\times(n-1)$ words. These words are made up of a set *W*. We wish to assign the color primitives of *P* to the matrix M so that there are no two identical words in the matrix, i.e.

$$W = \left\{ w_{ij} \middle| \begin{array}{l} w_{ij} \neq w_{kl}, (i,j) \neq (k,l), \\ 2 \leq i,k \leq (m-1), \\ 2 \leq j,l \leq (n-1) \end{array} \right\} \tag{2}$$

Furthermore, every element has a different color from its adjacent neighbors in the word, i.e.

$$M = \left\{ x_{ij} \middle| \begin{array}{l} x_{ij} \neq x_{i-1,j}, x_{ij} \neq x_{i+1,j}, x_{ij} \neq x_{i,j+1}, x_{ij} \neq x_{i,j-1}, \\ 1 \leq i \leq m, 1 \leq j \leq n \end{array} \right\}. \tag{3}$$

In this way, each defined location is unique and thus correspondence will be no problem. That is, if the pattern is projected onto a scene, and the word value for an imaged point (*u, v*) is determined (by determining the color of that imaged point and the colors of its imaged 4-adjacent neighbors), then the corresponding position (*i, j*) in M of this imaged point is uniquely defined. Of course, in addition to having each word of M be unique, we also wish to optimize the color assignments so that matrix M is as large as possible.

Another problem should be considered in the assignment. Because there are only three primary colors, the color pattern should be divided into several distinguishable color codes. To reduce the complexity of identifying color codes of a grid point among its neighbors, every two color codes should have enough distance. This requires a tradeoff between the number of color codes and the average code distance. The white color should be utilized mostly for segmentation of neighbor grid points so that the pattern will produce maximum image irradiance values.

According to the perspective transformation principle, the image coordinates and the assigned code words of a spatial point corresponded to its world coordinates. We can establish such a mapping relation between an image point in the image coordinate system and the spatial point in the world coordinate system. *X, Y,* and *Z* are the coordinates of a world point, corresponding with the image coordinates *u, v* and *x, y*. Together with the system calibration parameters, the 3D information of the surface points can be easily computed. Effectively, this can guarantee that the measurement system has a limited cost of computation since it only needs to analyze a small part of the scene and identify the coordinates by local image processing. Therefore the acquisition efficiency is greatly improved.

D. Code Generation Method

First, with a given color set P, we try to make a longest horizontal code sequence,

$$S_h = [c_1,\ c_2,\ c_3,\ ...,\ c_m]. \tag{4}$$

where *m* is the sequence length. For any adjacent color pair, it satisfies

$$c_i \neq c_{i+1}, \quad 1 \leq i < m, \tag{5}$$

and any triplet of adjacent colors, $\mathrm{T}_{h3i} = [c_i \quad c_{i+1} \quad c_{i+2}]$, is unique in the sequence,

$$\mathrm{T}_{h3i} \neq \mathrm{T}_{h3j}, \quad i \neq j,\ 1 \leq i, j \leq m-2. \tag{6}$$

The maximal length of the horizontal sequence S_h can be proved to be: *Length*(S_h) = p(p-1)(p-1)+2. Such a sequence can be generated by a random-search algorithm. In this project, all numbers of colors less than 32 were tested and every color set can generate a chain with its maximum length. Since the sequence is generated offline only once and will not affect the real-time performance, not pay much attention was paid to improving the searching algorithm.

Second, with given a color set P, we try to make a longest vertical color sequence,

$$S_v = [c_1,\ c_2,\ c_3,\ ...,\ c_n]. \tag{7}$$

where *n* is the sequence length. For any adjacent color pair, it not only satisfies condition (5), but also satisfies the requirement of being unique in the sequence,

$$[c_i \quad c_{i+1}] \neq [c_j \quad c_{j+1}], \quad i \neq j,\ 1 \leq i, j \leq m-1. \tag{8}$$

With unique adjacent color pairs, the maximal length of the vertical sequence S_v is: *Length*(S_v) = p(p-1) +1. And such a vertical sequence can be generated in the following way.

$$S_v = [1\,2\,1\,3\,1\,4 \ldots 1\,\mathrm{p}, 2\,3\,2\,4 \ldots 2\,\mathrm{p}, \ldots, (\mathrm{p}-1)\,\mathrm{p}, 1]. \tag{9}$$

For the reason that this vertical sequence will be used for modulo operation with the horizontal sequence, the digit *p* cannot appear in the vertical sequence. Therefore, the color number for the vertical sequence is actually one less than the horizontal sequence. If the *p* color is used to generate the horizontal sequence, p-1 digits are used to generate the corresponding vertical sequence with a (p-1)(p-2)+1 length.

Finally, the matrix for color projection can be generated by the maximal vertical and horizontal code sequences (S_h and S_v). This produces a matrix with the size (p-1)(p-2)+2 by $p(p-1)^2+2$ which is the maximum possible size for each codeword being unique in the matrix. The first row in the matrix can be defined by S_h. A second row is created by adding the first element of S_v to each element of S_h modulo p, where the modulo operation is only on the set {1, 2 . . . p} and does not include the 0 element as does the traditional modulo operation. Create a third row by adding the second element of S_v to each element of S_h modulo p. In this way, for a 4-color set the construction is an 8×38 matrix. If we define it $S = S_h \otimes S_v$, it can be proved that according to definition (1) each word in the matrix *S* is uniquely located.

The above-mentioned method formulizes the generation of a special code matrix which satisfies conditions (2) and (3). This generation scheme is a finite automaton: after the first row is defined, a following row is generated by a number of transitions jumped from its above row. However, this scheme has two drawbacks, one is that the matrix sometimes has the shape a 'long band' which is not what we want. For example, a 4-color set generates an 8×38 matrix, a 5-color set generates a 14×82 matrix, a 6-color set generates a 22×152 matrix, etc. The practical digital projector usually has an image with 4:3 or 16:9 for width:height. Therefore, we desire to generate a matrix with that shape or a square shape. While it is still difficult to mathematically generate such matrices by a formulation, this paper solve this by computer simulation. A program is implemented to find a maximum square matrix using a random-search algorithm.

III. 3D Reconstruction

A. Estimation of Pattern Resolution

The pattern resolution represents the number of grid points along a unit pixel in the image. It is important to estimate the area size of a grid point in a captured image for decoding the coordinates from the light pattern. One solution is to analyze the frequent characteristics in the image, e.g. by Fourier transformation. However, this causes extra computation cost and is not very suitable for real-time applications. The other way is to estimate the grid size directly from the structure of 3D vision sensor itself, even immediately after it is calibrated. For instance, if a structured light system contains one projector and one camera and they are located at a similar distance from the scene, we can compute it as in the following.

From the projector, the length of an illuminated line in the projected scene by a horizontal scanning line from the lighting device (e.g. LCD) is $L = 2Z\tan(\alpha_p/2)$, where Z is the scene distance, α_p is the viewing angle of the projector, and L is the line length projected on the sensor's X-Y plane.

The unit length corresponding to the L contributed by one pixel of the projector is $L_u = LP_u/N_p$, where P_u is the pixel width of the projector's lighting device, N_p is the number of pixels on one scanning line (currently usually 1024).

To the camera, the projection angle of L_u to the image is nearly $\alpha_{cu} = \tan^{-1}(L_u/Z)$.

The number of image pixels occupied by α_{cu} is

$$N_{cu} = \frac{\alpha_{cu}}{\alpha_c}N_c = \frac{\tan^{-1}\frac{L_u}{Z}}{\alpha_c}N_c = \frac{\tan^{-1}\frac{LP_u}{ZN_p}}{\alpha_c}N_c = \frac{N_c}{\alpha_c}\tan^{-1}\frac{2P_u\tan\frac{\alpha_p}{2}}{N_p} \quad (10)$$

where α_c is the viewing angle of the camera, and , N_c is the number of pixels on one scanning line. Note that the Z has disappeared in the end (10). This means the grid size on the image is independent from the scene distance and surface orientation. It is only dependent on the sensor structure. Taking a a practical vision sensor as example, if $N_c = 640$, $N_p = 1024$, $\alpha_c = 18^o$, $\alpha_p = 22^o$, $P_u = 25$, we have

$$N_{cu} = \frac{640}{18}\tan^{-1}\frac{2*25*\tan 11^o}{1024} = 19.33 \cdot$$

It means that when a 25×25 grid point is projected on the scene and received by the camera, it occupies about 19.33×19.33 = 374 pixels (probably not in a regular square).

B. Flood Search for Pattern Recognition

First, we need to find a seed word in an unknown area of the captured image. This can be implemented in the following way. First, randomly generate a position in the image. The color at this position should not be black. Then, find the square grid point at that position. A color similarity measurement is used to search a quadrangle in which colors are changing slightly compared with those outside.

The grid point is set to be the centroid of this quadrangle. And based on this grid point, we try to locate its four adjacent neighbors. Simply set the offset to be the gridsize determined in the above subsection, initialize the left, right, above, and nether points and determine the four square areas. If this grid point is found not to be regular, or any one of the four neighbors is not located, a new initial position should be generated. Finally, the coordinates of the seed word are determined according to the five grid points by corresponding their color codes in the pattern matrix.

Then, with the known grid size and initial seed word, it is easy to find all adjacent words by a flood search algorithm. It firstly tries to search several grid points around the seed word, and then to search more grid points near the known area. Each point to be added in the known partial net has to satisfy three conditions – its color, size, and regularity.

Since the color measured in the image is often not ideal regarding the distortion in the vision system and scene reflection, we decide it by a color likelihood function. The image pixel is compared with all the ideal colors in the coding set. If the desired code color corresponds to one of the two or three largest likelihood values, the grid point is accepted in the net.

Finally, net amendment and grid interpolation procedures are developed in this paper for the optimization of 3D results. The projection of the coded pattern should result in a regular net. However, due to the complexity of the scene and uncertainty in image processing, the constructed grid matrix could have some faults (namely holes and leaves). To correct these faults, this research develops a Net Amendment Procedure to find and amend them. For some cases, it can decide directly whether "insertion" or "deletion" is necessary to amend the net. Under a few other conditions, such an operation has to be determined according to its actual image content and with a likelihood measurement.

After all possible code words have been identified from the image, it is easy to compute the 3D world coordinates of these points since the coordinates on both the image and the projector are known. This yields a rough 3D map of the scene. In order to improve the resolution, we may perform an interpolation algorithm on such a map. Dependent on application requirements, the interpolation may be only on the segment of two adjacent grid points or inside the square area formed by four regular grid points.

IV. EXPERIMENTS

To implement the coding idea in a practical vision system and analyze the performance, we have to consider many other factors and conditions. In fact, this method has to be integrated with other techniques and algorithms for automating the modeling process, such as system calibration, image processing, 3D representation, visualization, etc. Thanks to considerable fundamental works on computer vision in our early projects, the experimental system is convenient to be set up again for this project.

Figure 6. The testing system in our laboratory

The vision system in our lab is a structured light system with a projector and a camera (Fig. 6). A 32×212 pattern generated from a 7-color set is used to illuminate the scene. The grid size is estimated to be 25×25 pixels. In the experiments, a seed word was identified randomly and other neighbor points are found by a flood-search algorithm [17]. The net was then amended by detecting isolated holes and abnormal leaves. Repeating the work until no large area is possible to yield more points, the whole net can be merged from them. Finally, the 3D mesh was reconstructed after performing 3D computation. A typical example is illustrated in Fig. 7. This paper used a Performance Analyzer (a program development tool) to analyze the time spent on some important procedures. Results show that 3D reconstruction in low-level or mid-level resolution (only computing the 3D coordinates on grid points or grid edges), takes about 100 ms. That speed is adequate for most applications.

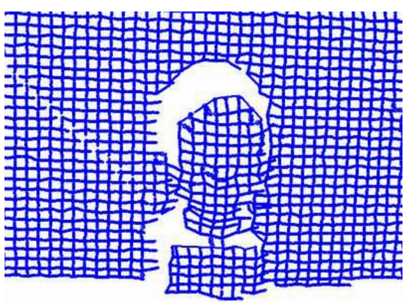

Figure 7. Result of 3D computation

V. CONCLUSION

A method for generating an encoded colored light pattern for fast 3D vision perception by a structured light system was employed in this paper. For a given set of color primitives, the patterns generated are guaranteed to be as large as possible with the restriction that each word in the pattern matrix must be unique. By using such a light pattern, correspondence is solved within a single image and therefore this is applicable in a live environment. Furthermore, the method does not limit the smoothness of object surfaces since it only requires analyzing a small part of the scene and identifies the coordinates by local image processing, which greatly improves the 3D reconstruction efficiency. Typically acquisition of a 3D surface with mid-level resolution takes about one hundred milli-seconds which is adequate for many practical applications. Further optimization of the program can improve the possible speed to about 30 frames per second.

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