Research on Phase Unwrapping Based on Color-coded Light technique

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***Abstract*—Optical three-dimensional (3D) measurement technology is one of the most active research topics in computer vision. Based on the theory of phase shift processing and color-coded light, a new unwrapping method which can measure the 3D-body with a high speed was proposed. First, the period distribution was got by the 4 bits binary-coded color pattern projection technology; then the phase collapsed in the range $(-\pi, \pi)$ can be obtained with the method of four step phase shift; finally exact phase can be computed by combining the phase shift processing and color-coded light method. The experimental results proved that the new method can reduced the number of the coded light and the true, exact phase can be obtained, and the 3D measuring speed can be highly improved.**

Keywords-Binocular vision, 3D measurement, Color structured light, Phase unwrapping

I. INTRODUCTION

The 3D color measuring technique based on the structured light phase shift has became a active research field with it's advantage of fast, accurate when measuring geometric dimensioning[1]. The technique based on the principle of light interference can provide non-contact measuring and the 3D information of scene[2], which can meet the requirement of modern advanced manufacturing. According to the number of cameras used in the system, there are two kinds of measuring technique, one is called monocular mobile method, and the other is called binocular stereo vision. Binocular vision optical measuring systems which based on phase projection have been widely applied in geometry amount of size detection, terrain mapping, precision parts or product 3D shape testing and other fields.

II. SYSTEM COMPOSITION AND MEASURING PRINCIPLE

A. System composition

The measuring system is shown in figure 1. The system is composed of a projector, binocular COMS cameras and computer data processing system. Sinusoidal vector light be projected on the surface of the tested object first, then cameras collected the deformation stripe image which is modulated by object heights. And the light intensity deformation is expressed I(x,y). The numerical value of phase shift can be computed by the computer with the images containning stripe information captured by the cameras.

B. Principle of phase shift method

Light interference theory is the base of time domain phase measurement profile, and it is also one way of the two typical structural lighting methods. The stripe information which is got by camera can be expressed as I (l x, y) [3]:

$$I_n(x,y) = R(x,y)\{A(x,y) + B(x,y)\cos[\phi(x,y) + \delta_n]\} \quad (1)$$

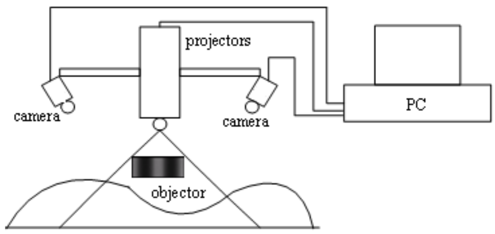

Figure 1. The 3D measurement system with phase fringe projection based on binocular vision

In formula (1), n represents the N frame fringe （n=1,2……N-1）, $I_n(x,y)$ means the light intensity which the cameras received. $R(x,y)$ represents the reflectivity of uneven surfaces, $A(x,y)$ represents the light intensity of background. B(x,y) represents the amplitude of stripe. $B(x,y)/A(x,y)$ represents the stripe contrast. δ_n represents the additional phase shift value. The phase $\phi(x,y) + \delta_n$ includes the information of surface shape of the object. Their specific relationships depend on the parameters of system structure. Phase shift algorithm is often used to calculate the phase. Phase shift algorithm is a very important role of phase shifting method in contour art. In this paper, in order to eliminate fixed noise in the interference field, nonlinear of array detectors and uncertainty of phase control, etc. Four-step phase shift algorithm is often used in practice. According to the least square principle, we can get:

$$\phi(x,y) = arctg\frac{I_3(x,y) - I_1(x,y)}{I_0(x,y) - I_2(x,y)} \quad (2)$$

In formula (2), I0，I1，I2，I3 represent the four interference patterns when the deltas of Phase mobile is π/2， and δ0 is 0. Because interference processing technology of anti-tangent function is introduced, the phase distribution $\phi(x,y)$ is wrapped around in the range of principal value $[-\pi, \pi]$ of anti-tangent function. Namely the range of the phase distribution which can be calculated in -π~+π or +π~-π abrupt change, this is called wrapped phase. So in order to calculate the high distribution of the object to be tested using phase function, we must change the wrapped phase to their original phase distribution. This process is called unwrapped or phase unwrapping.

III. TRADITIONAL TECHNOLOGY OF PHASE SOLVING

The algorithms of unwrapped phase are the key point in the process of interference patterns. They are used to get the real phase distribution from the unwrapped phase. Therefore domestic and overseas scholars put forward many unwrapped phase algorithms, roughly three algorithms are summed up, that is residual gap method based on residual point certain integral line method, path irrelevant algorithm based on the least-square principle and phase unwrapping algorithm based on network flow[3]. At present, projection gray-encoder are mostly used to unwrap phase in 3d measurement products of domestic companies. In order to get the pixel real phase Φ, we need project a group of six pictures gray coding light[4], Gray coding shows in figure 2[5].

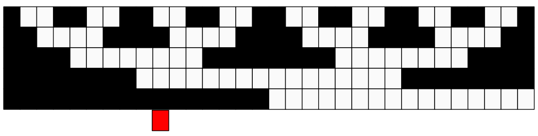

Figure 2. The sketch map of GRAY coding and decoding

In figure 2, According to the gray of each point in different image is encoded, each area can be expressed by a different five binary coding. For example, red square area, in five grating figure, 0 expresses back, 1 expressed white, thus, red square area in grating figure can be expressed as black, white , white , black and white, so the area for GRAY coding is 01101.The process of decoding firstly convert to binary code, then convert to decimal encoding, we can get that the cycle of red square is the ninth cycle. When we got its phase cycle, it can be combined with the phase principal values. This can be calculated real phase values of or each point.

After being decoded, we can get the point cycle K, calculate the phase principal values ϕ, receive real phase $\Phi = 2K\pi + \phi$ [6], at last. We must pay attention to two points. The first, a minimum width of coding cycle is required to consist with the width of the principal values. The second point is that choice of the number of color-structured light of gray coding is key technology. If the picture projection is less, than the phases which are computed are similar, so it isn't easy to distinguish them. But if the number of the pictures is more, the area of last segment is very small, thus it is inconvenient to cause the errors of GRAY decoding, when we process the image. So it is very important to choose the number of picture.

IV. UNWRAPPING PHASE TECHNOLOGY OF COLOR ENCODING LIGHT

According to colorimetric theories， color can be quantitatively measured，thus it is possible to measure 3d information using encoding color. There are a lot of color coding methods. For example, linear wavelength coding, digital color coding, Color combination coding. In this paper, we use four-digit color coding to code, and use three colors, green, and blue to combine, so that we can get white, red, green, blue and their complementary color: Black, green, product color. There are total eight kinds of pure color. We use four stripes to respectively represent binary 2^3 , 2^2 , 2^1 , 2^0 ,so that there are 16 different combinations. Because each group has four stripes, so we can use color-structured light of 64 stripes which we receive, to divide light field 64 parts. Thus we can replace GRAY coding pattern six times, then combine with phase shift digital light to reduce the number of light projection, and meanwhile we can achieve the same matching effect, greatly improve scanning speed. When we measure budging objects such as face, hands, the cup, we can achieve very good result.

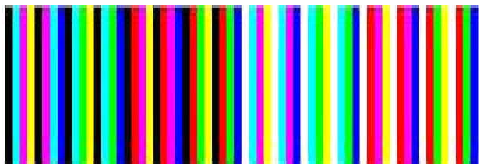

Figure 3. 4 bits binary-coded color

When we use color-structured light to 3d measure, there is some partial color in degree, because there is bottom color of the tested object. The color resolution is directly related to the application and accuracy of this technology. HIS format is another kind of color format, which I represent brightness or intensity, that is mean the extent of light and shade of the surface; S called saturation degree or white degree, the ingredient of white light color. H called chromaticity, it represents the closest spectrum color.

The definition of brightness (I) is basically the same in HIS entire format, it usually is the average of the three component RGB. It can be defined as: $I = (R+G+B)/3$; We will define that the smallest of the three components the RGB color image is white light weight, than divided by brightness values, we can quantitatively descript the degree of the white color which contained in this color. S represents White degrees, is expressed as $S = \min(R+G+B)m/I$. H can be defined that anyone color can be expressed as the combination of white color composition and spectral ingredients in RGB color format. And anyone spectral color can be defined the ratio of two colors in RGB format. We first remove the white light component, when we process the non spectral color in color image. That we use the minimum value of RGB three components minus two other components, we can get the spectra of the pixels. Then we determine the chroma according to the ratio of the two components [7]。

$$
\begin{cases}
\max(R,G,B)=R.,\ \min(R,G,B)=B,\ H=(G-B)/(R-B) \\
\max(R,G,B)=G.,\ \min(R,G,B)=B,\ H=2-(R-B)/(G-B) \\
\max(R,G,B)=G.,\ \min(R,G,B)=R,\ H=2+(B-R)/(G-R) \\
\max(R,G,B)=B,\ \min(R,G,B)=R,\ H=4-(G-R)/(B-R) \\
\max(R,G,B)=B,\ \min(R,G,B)=G,\ H=4+(G-R)/(B-G) \\
\max(R,G,B)=R,\ \min(R,G,B)=G,\ H=6-(G-R)/(R-G)
\end{cases}
$$

H is only relevant with itself characteristics of color, not relevant with the brightness of the image. According to this definition method, we adopt six colors evenly distributed at 0 to 6 six integer domain, calculate color images which we collect, using the transformations of HIS model to RGB model. Then H can be calculated, at last, value of the color can be calculated by comparing the numerical value. Code can be settlement according to color code lists. Then we get the cycle K of the point after being decoded, similar as GRAY coding, which is 64 independent cycles. We can get real phase $\Phi = 2K\pi + \phi$ with the phase shift grating, at last get uniform and dense point cloud through stereo matching.

V. Experiment and Analysis

Industrial color kinescope camera (COMS) using in the experiments is provided by DaHeng companies with resolution of 1280 * 1024 pixel and focal length of 12mm. The projector DX-320 was adopted and its brightness is 2500 lumens，which is produced by mitsubishi. Parameters of cameras can be got by calibration method proposed by Zhangzhengyou(Table 2). First projected four binary code (figure 4) structure light Gray coding, instead of the function of the surface into objects, and then also 64 area projection four phase shift stripe (figure 5), are calculated using the phase solution package, calibration parameters of 3d stereoscopic matching get objects point cloud (figure 6).

Figure 4. bits binary-coded color pattern projection

Figure 5. Phase-shift fringe

Figure 6. The points cloud with stereo matching

We only use projection information of one digital light to divide the site to achieve the same results of gray-encoder, through color information of color structure light. Thus we greatly reduced the number of digital light projection, and we improved the speed of the system scanning.

Color separation algorithm is good or not, and it will effect quality of the digital chromatic stripe. Due to the existing bottom color of the object to be tested, there is some partial color in degree when we measure the images. The technology of color resolution is directly related to the application and accuracy of the method.

The traditional phase unwrapping technology is the combination of gray coding and phase shift. It need project the image of six gray encoders to part the light field into 64 cycles. In order to facilitate decoding the binary of the image, we generally need project a black structure light and a white structure light, and we also need the information of four steps phase shift grating. There are twelve pictures totally. Thus it is very favorable when we measure the human or not too easy long remaining stationary objects. While we use color structured light to unwrap phase, we only need a picture structured light color, which can be instead of eight picture gray-encoder structure light. The time greatly decreased, it shortened for original half time, and we also can get point cloud of the measuring objects.

VI. SUMMARIES

In 3D optical measuring system, the traditional unwraping phase is based on gray-encoder. The drawback of this method is that many sets of structure light should be projected, which result in time consumming. In order to solve this problem, we provided a new phase unwrapping technique, which is based on four bit binary structure light color. We receive the measured object's phase periodic by using light color coding structure. The number of the grating projection can be reduce to half, and we can get principal values by combining four steps phase shift method, and then quickly get the real phase of the measured object $\Phi = 2K\pi + \phi$. Finally, we can got the 3D color point clouds of the object with the technique of camera calibration and image matching. Experiments proved that, this method greatly reduces the number of the structure light projection, and also quickly get a real and accurate the absolute phase.

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TABLE I. 4 BITS BINARY-CODED

decimal	Binary	Coding color	decimal	Binary	Coding color	decimal	Binary
0	0000	KCMY	8	1000	WCMY	0	0000
1	0001	KCMB	9	1001	WCMB	1	0001
2	0010	KCGY	10	1010	WCGY	2	0010
3	0011	KCGB	11	1011	WCGB	3	0011
4	0100	KRMY	12	1100	WRMY	4	0100

TABLE II. PARAMETERS OF CAMERA CALIBRATION

	Focal length	Image center	Image scale factor	Distortion coefficient
Left camera	12.18	649.910,455.753	-1.6036	-0.037，-0.215
Right camera	12.12	655.18，454.816	-0.93636	-0.0672, 0.1153
Left camera to right the camera rotational matrix		0.8628743 -0.010071 -0.505317	0.016787 0.99981 0.008738	0.5051393 -0.0160231 0.8628876
Left camera to right camera translational matrix		-371.8360	7.43987	86.926255
right camera to left translational matrix camera		364.8474	-1.95576	112.9423