# Novel Single Shot Structured Light Technique for Accurate, Reliable and Dense 3D Shape Measurement

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## ABSTRACT

Sinusoidal Structured Light Techniques (SSLT) are in wide spread use for 3D surface profile measurement of diffusively reflecting objects. Though they are capable of providing high-resolution surface profile data, for the results to be accurate and reliable they require large number of input images (especially if the objects under investigation possess *surface discontinuities)*. On the other hand, another class of structured light techniques (SLT), namely Color-coded Structured Light Technique (CSLT), is capable of providing reliable 3D shape reconstruction from a single image. But the accuracy and resolution of the measurement are very poor as compared to SSLT. As of today, to the best of our knowledge, there is no technique that is capable of providing simultaneously accurate, reliable and dense 3D surface profile from a single image of the objects with surface discontinuities. Growing importance of real time 3D shape measurement in diverse fields demand for the development of 3D shape measurement techniques with as minimum number of input images as possible (Ideally one image). This paper proposes a novel technique that can perform accurate, reliable and dense 3D-shape measurement from a single image. A novel design of the color-coded pattern is proposed. Mechanisms of (1) Extracting the Grayscale sinusoidal fringe pattern from the recorded image of the object (captured under the illumination of the proposed pattern) (2) calculating wrapped phase of it (this can provide dense 3D data with further processing) and (3) unwrapping this phase map with the help of the color content of the same image (this facilitates reliable reconstruction from a single image) are presented.

**Keywords:** Shape measurement**,** fringe pattern, phase unwrapping, color-coding, FFT analysis, surface discontinuities.

## 1. INTRODUCTION

The measurement of surface shape by use of projected structured light patterns is a well-developed technique. In this sinusoidal fringe pattern projection method is most widely used owing to its simplicity, accuracy and high resolution measurement capabilities. It allows the measurement of topographical variations of the object surface based on the retrieval of phase information encoded in the fringe pattern. Fourier transform[1], phase stepping methods[2] are the best popular fringe analysis techniques used to calculate the underlying phase distribution of the deformed fringe pattern. A major obstacle that frustrates the use of sinusoidal structured light projection technique is that the recovered phase using afore mentioned fringe analysis techniques is mathematically limited to the interval $[-\pi, \pi]$ corresponding to the principle value of arc tan function. In general the true phase may range over an interval greater than $2\pi$ in which case the recovered phase contains artificial discontinuities. Unwrapping these discontinuities is a matter of adding an appropriate integer multiple of $2\pi$ to each pixel element of the wrapped phase map. Normal phase unwrapping is carried out by comparing the phase at neighboring pixels and adding or subtracting $2\pi$ to bring the relative phase between the two pixels into the range of $-\pi$ to $\pi$. This causes problem when the technique is applied to real objects in engineering or medical measurements, because such objects contain edges or discontinuities that cause the true phase jump between any two pixels lay out side this range. It can then become impossible to unwrap correctly across such real discontinuities and large (multiples of $2\pi$) phase errors can propagate across the image.

To overcome this problem several phase unwrapping strategies were developed. Temporal phase unwrapping[3], Reduced temporal phase unwrapping[4], Spatio-temporal phase unwrapping[5] and Frequency multiplexing[6] procedures are the popular ones. However, to perform phase unwrapping, all these methods mandataroly require multiple phase maps generated by varying the spatial frequency of projected fringe pattern either linearly or exponentially. Further, the degree of reliability varies from method to method.

A different class of structured light projection techniques relies upon color-coded projection. In contrast to sinusoidal structured light projection, color-coded projection technique does not involve any phase unwrapping process. The color-coded illumination of the object supplies an additional degree of freedom that is necessary for measuring a surface profile. Limitations of this method are the spatial resolution of the measurement is far less than the fringe projection method, measurement is discontinuous in one of the directions and fineness of measurement in that direction is approximately equal to the width/pitch of the bands used in projection[7].

There have been some reports on using color as a means to boost the profiling speed while keeping the high resolution of fringe projection technique[8]. In this context *multichannel approach* (that uses interlaced RGB sinusoidal pattern) is effective in reducing the number of frames required by thrice compared to conventional procedures, but still multiple phase maps are required for reliable unwrapping of objects with surface discontinuities[9]. Moreover, previous experimental results showed that the measurement accuracy of this technique was lower than that of the traditional Gray scale technique due largely to color coupling and imbalance problems.

Authors have reported a new strategy of profiling objects with surface discontinuities in Ref [10] that requires only two images of the object – one captured under the illumination of sinusoidal fringe pattern and the other with color-coded pattern. Wrapped phase map calculated from the first image with FFT analysis is unwrapped with the help of information extracted from the later image. Thus reliable, accurate recovery of surface profile at high resolution of measurement from only two images was demonstrated.

The main interest of this paper is to report a novel structured light technique that is capable of providing accurate, reliable surface profile of object (even with surface discontinuities) at high resolution of measurement from a *single image*. Details about the design of the pattern used for illumination and processing mechanisms adapted to calculate wrapped phase map and then to unwrap it are presented.

## 2. METHOD

### 2.1. Design of the pattern used in the proposed single-shot method

In Ref [10] two pattern are projected on to the object. One is sinusoidal fringe pattern – from this wrapped phase map can be obtained (this gives high resolution surface profile). Second one is a color-coded pattern – information extracted from this used in reliable unwrapping of the phase map thereby providing both reliable and high resolution surface profile of objects even with surface discontinuities. *Aim of this new design is to combine the features of above two patterns in to a single one*. This is achieved by introducing the intensity (value) modulation with in each color band/stripe of the color-coded pattern used. Thus the sinusoid of intensity is embedded in the value channel and the colored stripes are embedded in the hue channel in HSV color space (See Fig. 1). This design helps in recovering the two separate image of the object: one is deformed sinusoidal fringe pattern and the other is deformed color-coded pattern from a single image.

The objective of the coding strategy is that, given an element of the pattern (a stripe), its position in the pattern can be obtained by inspecting a local neighborhood of elements around it. Therefore it is necessary to color all the elements of the pattern so that every neighborhood has its own combination of colors different to the rest. De Bruijn sequences are a mathematical resource which can achieve this aim. A De Bruijn sequence of order $m$ over an alphabet of $n$ symbols is a string of length $n^m$ that contains every substring of length $m$ exactly once (known as *window property*). De Bruijn sequences are widely used to color stripe patterns and multi-slit patterns by mapping every symbol of the alphabet with a certain color. The most powerful and developed technique in this field was presented by Zhang et al[11]. The De Bruijn sequence used was generated with the constraint that two consecutive stripes could not have the same color[11]. With such constraint, the length of a De Bruijn sequence decreases from $n^m$ down to $n(n-1)^{m-1}$. This same coding strategy is adapted in this paper along with an important modification introduced in to it.

Therefore, the projection pattern used for encoding the object in the present communication is a second order De Bruijn sequence generated using five basic colors that are equally spaced in hue space. The sequence essentially comprises of twenty labeled stripes, each of which is colored with one of the chosen basic colors. Further, no two consecutive stripes in the pattern have same color and consist of twenty uniquely identifiable color-transitions. The novelty of the design used for the color-coded pattern lies in introducing sinusoidal modulation in the Value/Intensity channel. Image of the color-coded pattern generated is shown in Fig.1.

While surface discontinuities at coarse resolution (equal to the width of each band $-f_0$) are reliably recovered by observing the deformation in color-coded stripes, grayscale sinusiodal intensity variation helps in height recovery at a fine resolution (of the order of $f_0/15$ or so) with FFT analysis. Thus achieving accurate, reliable and dense 3D recovery from a single image. Following section describes how to extract a deformed sinusoidal fringe pattern form the recorded color image and method used to calculate the wrapped phase map (this after unwrapping provides dense and accurate 3D data). But conventional methods of phase unwrapping require several additional images of the object to provide reliable results. However, the novelty of this method is to be able to unwrap this phase map with the help of the deformed color-coded pattern present in the same image.

**2.2 Calculating the Wrapped Phase Map**

Color-coded pattern designed as mentioned in the previous section is projected on to the object using an LCD projector and an image is recorded with an off the shelf color CCD camera from an off-set angle. The recorded image can then be fed into the computer and can be processed using MATLAB. First the image is converted from RGB image to HSV image, a three-dimensional matrix, using MATLAB command. First component in the third dimension of the matrix represents Hue, second component represents Saturation and third represents Value. Thus if we extract the third component, it is a two dimensional matrix representing intensity variations of the pattern on the object surface. As the value component of each band in the projected pattern is varied sinusoidally, the Value component of the recorded image (procedure to obtain this is mentioned above) consists of a phase modulated sinusoidal fringe pattern. The mathematical representation of the intensity profile of this image is given by:

$$g(x, y) = a(x, y) + b(x, y)\cos(2\pi f_0 x + \phi(x, y))$$

where *$f_0$ is equal to the number of bands used in the pattern,* $\phi(x, y)$ contains the desired information about the surface profile of the object and $a(x, y)$, $b(x, y)$ represent unwanted irradiance variations arising from the non-uniform light reflection by a test object. Phase distribution $\phi(x, y)$ is calculated using Takeda's method[1]. Phase obtained with this method is indeterminate to a factor of $2\pi$ (wrapped phase). Phase unwrapping is necessary to correct these discontinuities.

**2.3 Phase Unwrapping**

The object phase $\phi(x, y)$ calculated according to Eq.(5) is wrapped in the range $-\pi$ to $\pi$. The true phase of the object is $\varphi_{un}(x, y) = \phi(x, y) + 2\, n(x, y)$; where $\varphi_{un}(x, y)$, $\phi(x, y)$ are unwrapped phase and wrapped phase respectively. $n(x, y)$ is an integer. Unwrapping is only a process of determining $n(x, y)$. A conventional spatial phase unwrapping algorithm (CSPU) search for locations of phase jumps in the wrapped phase distribution and adds/subtracts $2\pi$ to bring the relative phase between two neighboring pixels into the range of $-\pi$ to $\pi$. Thus irrespective of actual value of $n(x, y)$ to be evaluated, they always assign $\pm 1$ thereby fails to reliably unwrap phase maps *in profiling objects with surface discontinuities* (where $n(x, y)$ can be greater than one). In order to determine $n(x, y)$ we are introducing the following procedure:

**2.3.1. Novel Unwrapping Strategy**

In this new approach, information contained in the Hue channel (color-coding) is used for calculating $n(x, y)$. For this first of all, every stripe in the deformed color-coded pattern has to be labeled. There are several ways to do that. In this paper following approach is used:

**2.3.2. Color edge detection and Labeling of pixels**

For each camera scan line (a row of pixels), we can localize color edges by looking for local extrema in gradients (1D derivatives) in each of the color channels (i.e. Red, Green and Blue channels) (See Fig. 5). In practice, however, this will lead to distinct localizations in each color channel. Instead, we compute the combined gradient function along a scan line that is comprised of the sum of the squares of the gradients in each of the color channels (Fig. 6). The edges are then determined to be local maxima of this function. And their strengths are the color gradient values at the localized edges.

However, aforementioned approach for color edge detection fails when the adjacent stripes are of same color (as there will not be any transition in any of the color channels). Though no two adjacent strips have same color in the projected pattern, if the object under investigation possess surface discontinuities (step height variations), it is likely that the two adjacent stripes in the deformed color-coded pattern can be of same color. In this case we decided to base the edge detection based on the phase variance (defined in [12]) of the image. The phase variance is a measure of how fast the phase of a pixel changes compared to its neighbors. A large chance in phase corresponds to a discontinuity in surface profile and is interpreted as an edge (though there is no difference in color of both the stripes). Even this procedure of detecting edge fails when the step height that produces a phase modulation of exactly multiple of $2\pi$ is present and the color of stripes on both sides of this discontinuity are same. In such cases edge detection is implemented in two iterations. In the first iteration, edges of first two aforementioned types are identified over the entire image. In the second iteration, spacing (i.e., number of pixels) between two consecutive edges is measured and if the count between any two consecutive edges exceeds a set threshold, then mid point of two such edges is identified as the new edge.

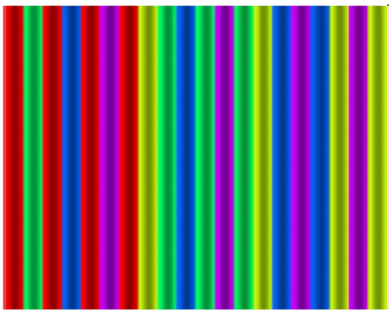

Fig.1 Color-coded pattern on reference plane

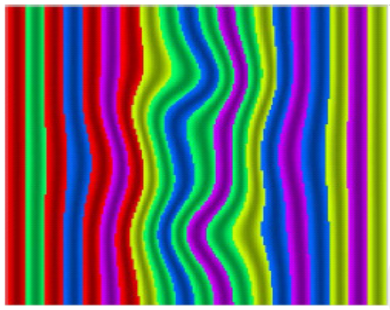

Fig.2 Deformed Color-coded pattern

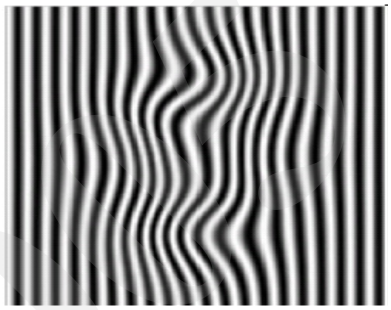

Fig.3 Fringe pattern extracted from Fig.2

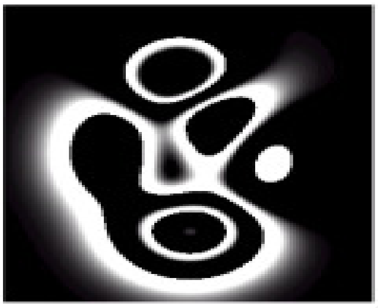

Fig. 4 Wrapped Phase Map

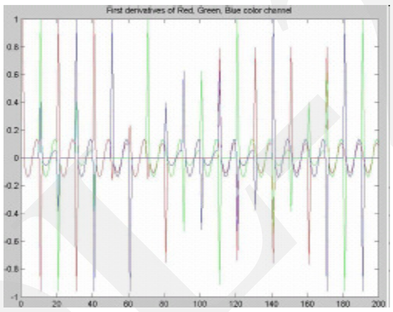


Fig. 5 Gradients in each color channel

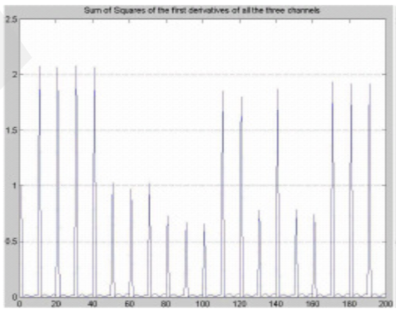


Fig. 6 Combined gradient function

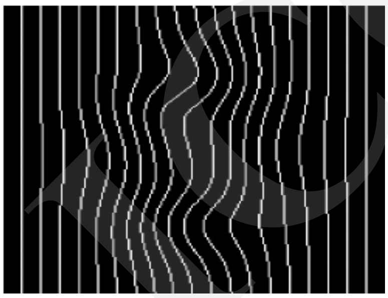

Fig. 7 Edge detected image

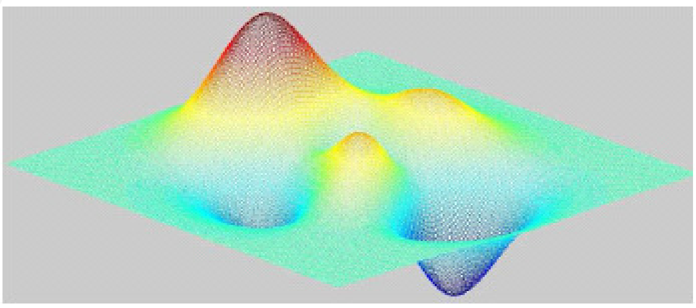

Fig. 8 3D surface plot of the reconstructed surface profile

Once edges are detected, by identifying each color-transition at all edges (as all color transitions are uniquely identifiable) one can label the two stripes on either side of each edge. After labeling all stripes, by calculating the difference of labels of two successive pixels, one can estimate n(x, y) for reliable unwrapping of the phase map as follows: n (x, y) = {l(x, y) – l(x, y-1)} – 1. Where l(x, y) is the label/index of pixel (x, y) in the image. Therefore unwrapped phase map is $\varphi_{un}(x, y) = \varphi(x, y) + \{[l(x, y)- (x, y-1)] -1\}*2\pi$ . Thus this method is capable of performing reliable unwrapping from a single image of the object captured under the illumination of the specifically designed color-coded pattern.

## 3. COMPUTER SIMULATIONS

To demonstrate the ability of the proposed approach in profiling objects with and without surface discontinuities, from a single image, two typical objects are simulated using MATLAB and their profiles are reconstructed. Fig. 1 shows the image of color-coded pattern generated using five colors with the help of De Bruijn sequence. Simulated object is 3D peaks distribution that is a function of two variables obtained by translating and scaling gaussian distribution (Fig.8). Image of simulated deformed color-coded pattern is shown in Fig.2. Converting the recorded RGB image to HSV image using MATLAB and separating the Value channel (i.e., third component of the HSV image) results in deformed sinusoidal gray scale fringe pattern (as shown in Fig. 3). Wrapped phase map of this pattern calculated using Takeda's method is shown in Fig.4. Fig. 5 shows gradient of each color channel along a sample scanline. Combined gradient function calculated along the same scanline is shown in Fig. 6. Location of edges is determined from the combined gradient function as described earlier (Fig.7). Three-dimensional surface plot of the reconstructed surface profile obtained by unwrapping the phase map is shown in Fig. 8.

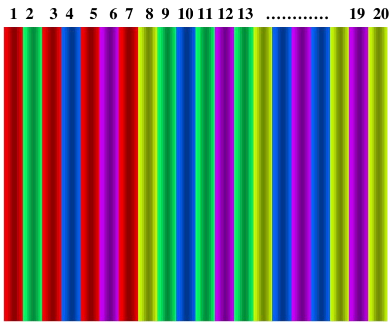


Fig. 9 Color-coding on reference plan ($C_0$)

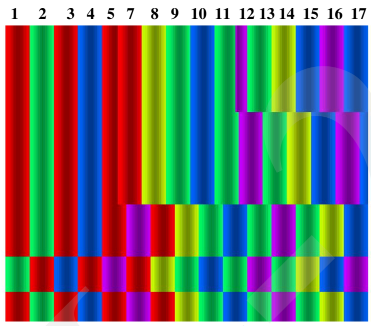


Fig.10 Deformed color-coded pattern ($C_r$)

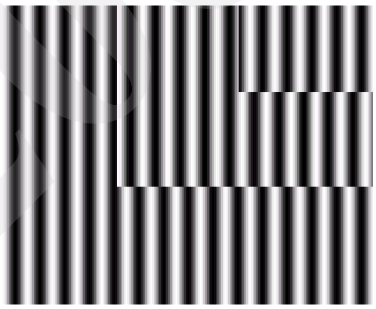

Fig. 11 Fringe pattern extracted from Fig. 10

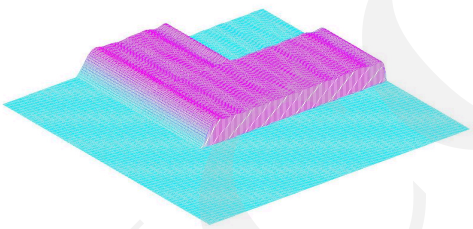

Fig. 12 Wrapped phase map

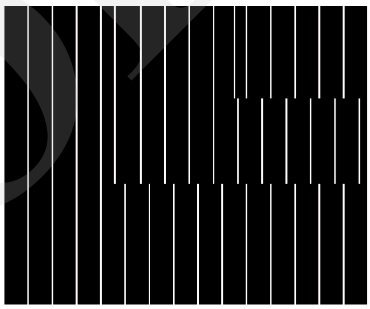

Fig. 13 Edge detected image

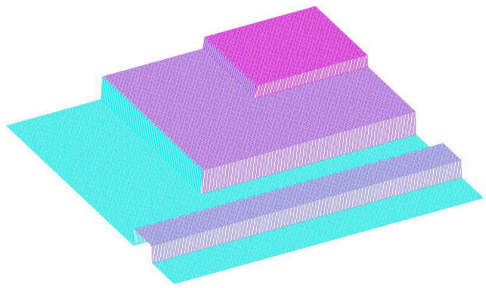

Fig. 14 3D surfce plot of Unwrapped Phase Map

Potentiality of this novel method can be appreciated if the object under investigation possess surface discontinuities. An object with surface discontinuities is simulated using MATLAB with three step height variations 8mm, 11mm and 32 mm as shown in Fig. 8. Corresponding phase modulations for the optical geometry considered are $2\pi$, $2.67\pi$ and $4\pi$ respectively. Fig.9, 10 show images of the simulated fringe pattern projected on to a reference plane and object surface respectively. Sinusoidal gray-scale fringe pattern extracted from Fig.10 is shown in Fig. 11. Wrapped phase map $\varphi(x, y)$ is calculated using Eq.(5) as explained in sec-2.2. Three-dimensional surface plot of wrapped phase map is shown in Fig. 12. It is impossible to unwrap the phase map in Fig. 12 correctly by spatial phase unwrapping techniques, because the phase jumps at the surface discontinuities are greater than or equal to 2π. Since estimating exact number of fringes shifted at each step height is not possible from Gray-scale fringe pattern alone (Fig.11), information extracted from the color-coded pattern is used to obtain reliable phase unwrapping. From the knowledge of observed color ($C_o$) and expected color ($C_r$), height deviation at every point on object surface can be expressed in terms of difference of their band indices/labels as explained in section. In the absence of any surface discontinuity the sequence in which the color bands appear on object surface is known from $C_r$. There will be a discrepancy in the sequence of appearance of bands only if there is a surface discontinuity (See Fig.10). Therefore, calculating difference of labels of successive pixels over the entire image enables us to identify the presence as well as exact location of surface discontinuities. Fig. 13 shows the image of the edge detected matrix that helps to label the bands and the 3D surface plot of the unwrapped phase map is shown in Fig. 14.

## 4. CONCLUSIONS

The novel structured light technique proposed in this paper, that combines concepts of color-coded projection and Fourier transform profilometry, is shown to provide accurate, reliable and dense 3D data from a single image. Successful unwrapping of the measured phase even in presence of surface discontinuities is demonstrated. Unlike temporal, spatio-temporal unwrapping and frequency multiplexing procedures, this new approach requires a single image of the object for surface profile measurement. It is shown to be *significantly faster and reliable* than temporal phase unwrapping that uses complete exponential sequence and compared to it the reduction both in image acquisition and in analysis times by the factor ($\log_2 f_0 + 1$) is an important advantage of the present approach.

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