Color profilometry techniques: A review

Técnicas de perfilometría en color: Una Revisión

Nadia Tornero-Martínez^{1,*}, Gerardo Trujillo-Schiaffino¹, Marcelino Anguiano-Morales¹, Paloma Guadalupe Mendoza-Villegas¹, Didia Patricia Salas-Peimbert¹, Luis Francisco Corral-Martínez¹.

1. Tecnológico Nacional de México / I. T. Chihuahua,
Ave. Tecnológico 2909, 31310 Chihuahua, México.

(*) E-mail: nadiatornero@gmail.com

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ABSTRACT:

Structured light is widely researched in tridimensional profilometry, due to its capability to acquire surface data from a series of images in a fast and reliable way. Hence a wide range of techniques are being used for such purpose, among which are the use of color to encode patterns. The use of color-coding provides the ability to obtain additional data from a single image, to achieve faster 3D reconstructions with higher resolution. In this paper, a new classification of color-coded structured light patterns is proposed, and a review of the techniques is presented.

Key words: Profilometry, structured light, color profilometry

RESUMEN:

La luz estructurada es ampliamente investigada en el área de perfilometría tridimensional, por su capacidad de obtener información de la superficie de un objeto rápidamente a partir de una serie de imágenes. Por lo cual existe una gran diversidad de técnicas que se utilizan actualmente, entre las cuales se encuentra el uso de color para la codificación de patrones. El utilizar codificación en color proporciona la capacidad de obtener información adicional de una sola imagen, para obtener reconstrucciones más rápidamente y con mejor resolución. En este artículo se propone una nueva clasificación para los patrones de luz estructurada en color y se presenta un resumen de las diferentes técnicas.

Palabras clave: Perfilometría, luz estructurada, perfilometría en color

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1. Introduction

Nowadays structured light techniques are widely used in profilometry to acquire rapidly 3D surface data from a single image or a series of captured images; they are considered one of the most reliable procedures to obtain 3D data, and their accuracy is constantly increasing [1, 2]. There has been extensive research on different methods and their results; therefore, a large variety of patterns can be found on 3D imaging.

Structured light techniques illuminate a surface with a single 2D light pattern image or multiple patterns; then an image or a series of images are acquired to analyze the projected pattern; if the projected and reference patterns are similar, then, the surface is planar, while if the patterns are distorted, the surface has an irregular topography. The distorted pattern can be analyzed with various methods to calculate the depth or height information. A basic profilometry system, as shown in Fig. 1, usually includes: an active device (projector), which projects a structured pattern onto a surface; an imaging sensor (camera), to acquire a 2D image of the surface under the projected pattern; and a unit processor (computer), to digitally design the structured pattern, and run the analysis of the projected pattern to find the 3D surface's data [1-10].

Fig. 1. 3D profilometry system.

There is an eclectic range of structured light techniques that are used in 3D imaging, and they can be classified according to either the type of projected pattern or the number of images taken. Multiple-shot

methods require the projection of various patterns onto a surface, therefore, a series of images of the projected patterns are taken, and single-shot are based on the projection of a single pattern, thus only one image is acquired. Some of the most renowned multiple-shot techniques are sequential projection such as: binary coded fringes and phase shifting patterns. Continuous varying patterns which implement color information into a unique pattern, thus known as single-shot, such as: rainbow 3D camera and continuously varying color code. Stripe indexing patterns are also single-shot, as color-coded fringes, grayscale-coded fringes, and De Bruijn sequence [4, 5].

The elected method of analysis depends directly on the projected pattern technique. Analysis for fringe pattern profilometry (FPP), can be primarily classified as: phase-shifting profilometry (PSP), and Fourier transform profilometry (FTP). PSP uses three or more pattern images for the analysis, where the initial phase is gradually shifted in each image. FTP uses a single image for the analysis, through high frequency carrier fringes [1, 5].

Although previous researches review different pattern projections and describe how to classify them, none is uniquely dedicated to color-coded patterns [4-10]. There is extensive research on recent color-coded techniques, therefore various methods have been proposed or improved. In this paper, an updated review of these and a new classification for color structured light is presented. The rest of the paper is organized as follows. Section 2 describes the traditional phase-shifting technique. Section 3 presents the proposed classification, a description of the procedures proposed by different authors. Section 4 encompasses the conclusions.

2. Phase-shifting profilometry

A series of sinusoidal intensity patterns are projected onto a surface, gradually shifting the phase of each pattern, as shown in Fig. 2. This technique usually requires the projection of at least three phase-steps onto a test surface, and a reference plane image [1-12]. Due to the height of the test surface, the pattern will be distorted. Estimating the difference between the reference plane and the distorted pattern provides enough information to reach a 3D reconstruction.

Fig. 2. Phase-shifting profilometry.

Different algorithms have been developed, such as: three-step, four-step, five-step, and others. The algorithms designate the number of equal phase-shifts that the pattern will go through [10].

Equation (1) describes the intensity patterns shifted by a factor of $2\pi/N$ from the previous projection, with N number of projections.

$$I_n(x, y) = I'(x, y) + I''(x, y)\cos(\phi + \frac{2\pi}{N}) \quad (1)$$

Where:

$I'(x, y)$ is the average intensity

$I''(x, y)$ is the intensity modulation, and

n is nth intensity pattern.

The phase to be solved is defined by $\phi(x, y)$ and can be obtained by equation (2).

$$\phi(x, y) = \tan^{-1} \frac{\sum_{n=1}^N I_n(x, y) \sin(2\pi n/N)}{\sum_{n=1}^N I_n(x, y) \cos(2\pi n/N)} \quad (2)$$

The calculated phase ranges from $-\pi$ to π , having discontinuities of 2π . A phase unwrapping algorithm is required to achieve a continuous phase; the phase range is extended from 0 to 2π , removing large discontinuities by adding or subtracting multiples of 2π . To retrieve good quality phase maps two conditions must be satisfied: the signal must be free of noise, and the absolute phase difference between two neighboring pixels must be less than π [11]. Fig. 3 demonstrates how the wrapped phase has larger discontinuities than the unwrapped phase.

Fig. 3. Phase unwrapping.

Once the unwrapped phase is attained, the phase can be converted to real height $z(x, y)$ based on the period of the sinusoidal pattern P , phase difference from object pattern and reference plane pattern $\phi(x, y)$, and the angle between camera and projector α [2, 10-14]. Equation (3) shows the assessment of the real height of a surface, and Fig. 4. shows the configuration parameters required for height estimation.

$$z(x, y) = \frac{\phi(x, y)}{2\pi} \frac{P}{\tan \alpha} \quad (3)$$

Fig. 4. Height estimation parameters.

Phase-shifting profilometry has its advantages, among them high resolution reconstructions, point by point measurement, and lower sensitivity to surface reflectivity and ambient lighting. Although it also has some limitations, such as multiple surface images are required, higher reconstruction time, strict system calibration, and ambiguity is presented when the test surface has discontinuities larger than 2π . To overcome the mentioned limitations, color techniques are implemented.

3. Color-coded techniques

Color-coded patterns are mainly used in single-shot methods, due to their proficiency to encode further information into three different color channels, and reduce the acquisition time. As a result of the increasingly improvement of cameras and projector technologies, parameters such as color range and true color have been enhanced, thus there has been a surge in the use of color-coded patterns in 3D imaging. In this section, a new classification of color-coded techniques, and a description of some are presented. Fig. 5

shows the suggested classification of structured light methods, the image acquisition options for each class, and an example of the pattern.

Fig. 5. Color-coded techniques classification.

3.a. Phase-shifting

Phase-shifting techniques have been frequently used in 3D imaging, because of their accuracy and speed, although, as it was mentioned before, some limitations are observed. In recent years the merging of color information has been increasingly used in an attempt to develop either a single-shot or multi-shot phase-shifting, able to encode supplementary surface data on an image or images to reduce the ambiguity presented in traditional grey-level phase-shifting on discontinuous surfaces [15-29].

Color phase-shifting techniques frequently use the three-step phase-shifting method since it requires the least number of projected patterns, although, other analysis can be applied. There are two ways to implement it, multi-shot and single-shot.

On single-shot techniques, multiple phase-shifted fringe patterns are encoded onto a single color pattern through the RGB channels, which is then projected onto an object whose surface will be acquired in a single color image. According to the topography of the tested area, the pattern will be distorted allowing to retrieve the phase of the object, and by extracting the color planes from the acquired image, three phase-shifted sinusoidal patterns are achieved. Then the traditional phase-shifting methods to retrieve the wrapped and unwrapped phases can be applied [15-24]. Fig. 6 illustrates the process of single-shot color phase-shifting.

Fig. 6. Color phase-shifting technique (single-shot).

The advantages of the single-shot phase-shifting techniques are high speed, the possibility to be used on dynamic surfaces, and real time topography measurements.

Also, these techniques reduce the ambiguity presented on the wrapped phase caused by discontinuous surfaces, leading to better reconstructions. Merging phase-shifting and color information leads to an infinite amount of pattern possibilities.

Even though ambiguity is reduced, a phase unwrapping algorithm must be implemented to remove discontinuities larger than 2π . A high quality projector and camera must be employed to achieve the best color projection and acquisition, so more surface data can be retrieved. The color crosstalk from the camera, overlapping similar wavelengths, can lead to the loss of surface data. The nonlinearity gamma from the projector can affect the phase unwrapping step. Color surfaces alter the projection, thus it's essential to have a neutral hue surface. A calibration is suggested to improve the color quality of the projection and acquired image. An absolute phase is not achieved, therefore, an unwrapping algorithm must be implemented.

Some of the developed single-shot color phase-shifting techniques are described next.

Huang *et al.* [15-16] encode three phase-shifted patterns with a phase shift of $2\pi/3$ through the red, green, and blue channels onto a single color fringe pattern as shown in Fig. 7. An image of the projected pattern is acquired; then its RGB components are extracted, creating three grey-level phase-shifted images. Using the three-step phase-shifting algorithm, the phase can be retrieved through Equation (4). The technique can only be used on surfaces of neutral hues, the presence of color affects the extraction of the phase-shifted patterns. Color crosstalk is present, thus a compensation of the overlapping of wavelengths is implemented on their research.

Fig. 7. Intensity modulation of a three-step color phase-shifted pattern.

$$\phi(x, y) = \tan^{-1} \left[\sqrt{3} \frac{I_1 - I_3}{2I_2 - I_1 - I_3} \right] \quad (4)$$

Yin *et al.* [17] use a similar encoding technique to the traditional phase-shifting method. Using a phase shift of $2\pi/3$, a set of three grayscale phase-shifted patterns are encoded in the RGB channels creating a single colourful pattern, which is projected onto a surface. A single image of the projected pattern is captured, and the color model of the image is transformed from RGB to HIS. The hue plane is extracted to obtain the unwrapped phase; and through a triangulation method the topography can be retrieved. The saturation and intensity planes are evaluated, to identify the abrupt phase changes presented at edges and shadowed regions; once the irregularities are located, they can be disregarded in the absolute phase map. This technique addresses: the retrieval of the topography of an irregular surface, the correction of crosstalk, and the projector's gamma nonlinearity.

Flores *et al.* [18] also present a similar procedure, based on the encoding of three phase-shifted fringes onto the RGB channels of a single color pattern. An algorithm to reduce crosstalk is proposed, along with an iterative algorithm to retrieve the phase with higher precision. Their approach can be implemented for dynamic objects. C. Je *et al.* [19] use the same pattern encoded onto the RGB channels. The technique focuses on the correction of the distortion between the projector and camera, reducing the nonlinearity of the projector and the crosstalk. The authors present an adjustment to smooth the distribution of the color phase and a phase unwrapping algorithm. Through their approach, the color or reflectance of a surface can be neutralized to obtain the unwrapped phase, achieving satisfying results even on colorful surfaces. Y. Hu *et al.* [20] also use a color three phase-shifted pattern. Studying the effects of crosstalk, they propose a method called blind color isolation to reduce crosstalk and waive the color calibration of the system. The system eliminates crosstalk, reducing the distortion of the acquired image a more accurate reconstruction is achieved.

F. Da *et al.* [21] proposed a technique that uses a single color pattern to improve the phase map results obtained with Fourier transform. Two sinusoidal fringe patterns with different frequencies are encoded onto the red and green channels of a color pattern, while the blue contains the averaged value of either channel. The pattern is projected onto a surface and a single image is acquired, which is then separated onto the RGB components. Through Fourier transform analysis the wrapped phase is retrieved from the red and green planes. The main modification is that the blue channel is subtracted from the red and green channels, thus eliminating the background and noise present in the image leading to an improved phase map for discontinuous surfaces. Phase unwrapping for two frequencies is applied, where the low frequency corrects the high frequency phase unwrapping. This technique is able to retrieve the 3D reconstruction through a single image for irregular surfaces, eliminating the background noise often presented in Fourier analysis. Padilla *et al.* [22] also use a single color phase-shifted pattern with Fourier transform analysis. Three sinusoidal fringes are encoded onto a single color pattern that is then projected onto a surface, and a single color image is taken. The authors study the measurement, effects, and correction of color overlapping when using different phase analysis techniques. Using a low-pass filter the projector's gamma nonlinearity is reduced, the linear crosstalk was calibrated and compensated. Bruning's three-step algorithm was tested, noting that when severe RGB crosstalk is present this analysis has great distortions, thus requiring further analysis. Reordering the acquired patterns, a higher frequency pattern is achieved and Fourier analysis can be tested; a phase-demodulation method was employed to filter the distortion presented in the spatial Fourier domain, removing undesired data. Through their analysis, better results are achieved after compensating crosstalk and using Fourier analysis. Skydan *et al.* [23] also explore the use of the Fourier

transform analysis on a single color image, though the technique is based on the simultaneous projection of multiple patterns from different angles to acquire surface data from a wider scene, as shown in Fig. 8. Two phase-shifted patterns are projected onto a surface from different projectors, using a different color on each pattern. Since each projector is placed at a different angle, a larger testing area is permitted, and shadows presented on irregular surfaces is reduced. The camera is usually placed orthogonal to the reference plane, while the projectors can have a 90° or 180° angle from each other's axis, but both have a small angle to the camera.

Fig. 8. System proposed by Skydan *et al* [22].

Castillo *et al.* [24] propose a new deflectometry technique where a single color fringe pattern similar to the one used by Huang *et al.* [15-16] is displayed on an LCD screen. The pattern is also created by a red, green, and blue phase-shifted fringes encoded on a single image. A CCD camera is placed orthogonal to the screen, and acquires an image of the fringe pattern. Then, a phase object is placed on the camera-screen's path, the fringe pattern is distorted and a single image obtained. The phase map is then calculated from the intensity values on each color plane through a proposed one-step unwrapping method.

By contrast, multi-shot techniques, combine a set of sinusoidal patterns with color information, these patterns are sequentially projected onto the surface using the different channels of the camera, and multiple images of the surface are acquired [10, 25-29]. The major advantage of these is that a higher resolution is reached, since more data is retrieved through the sequence of images, resulting in 3D reconstructions with greater quality. Although as with traditional phase-shifting, the use of multiple images increases the required processing and analysis, therefore, slowing the reconstruction time. Single-shot and multi-shot methods can be adapted into either capture mode. Fig. 9 illustrates the process of multi-shot color phase-shifting techniques.

Fig. 9. Color phase-shifting technique (multi-shot).

S. Zhang *et al.* [25-28] developed a technique using phase-shifted fringes to obtain a surface's 3D shape. A pattern is created encoding three shifted sinusoidal fringes into a single color image through the RGB channels. Through a DLP projector, the RGB planes of the color pattern are projected separately in sequence onto a surface; projecting three grayscale phase-shifted fringes. Two cameras are employed for image acquisition, a monochromatic camera captures each projected grayscale pattern, while a color camera captures a 2-D color image of the surface to subtract the texture. Through the traditional three-step phase-shifting method and unwrapping algorithm the phase map is retrieved. A modified analysis is presented which is called the 2+1 phase shifting algorithm, where two images of the fringe patterns with a phase shift of 90° and a flat image are taken, to retrieve the phase Equation (5) is employed. The use of the 2+1

algorithm can be employed on dynamic surfaces due to its high speed, reducing the number of images. The technique can also retrieve the texture of a surface through the color image, not only the 3D data.

$$\phi(x, y) = \tan^{-1} \left[\frac{I_1 - I_3}{I_2 - I_3} \right] \quad (5)$$

Z. Zhang *et al.* [29] describe the use of three phase-shifted color patterns with different frequencies encoded onto a single pattern through the RGB channels. Although this technique can be modified into single-shot mode through the Fourier transform, Zhang *et al.* implemented the four-step phase-shifting method. On each channel the pattern has a gradual phase-shift four times, a color image is taken with each shift, and then the four images are separated onto their RGB components, acquiring a total of twelve images that are subsequently analyzed to obtain the phase map for each channel. The work emphasizes on the measurement and correction of crosstalk presented on the junction of different colors, compensating the overlap of different wavelengths achieves 3D imaging with higher resolution.

López *et al.* [10] employed a sequence of color sinusoidal fringes and the phase shifting algorithm to acquire the topography of a surface, their system is shown in Fig. 10. A sequence of red, green, and blue phase-shifted patterns are projected onto an object. For each color, the four-step phase-shift is employed, thus acquiring four images with a phase-shift of 90°, and phase is retrieved through Equation (6). Using the information of the different images, the traditional shifting algorithm is applied to unwrap the phase of each image, and then the four results are averaged to obtain the surface's topography and color.

Fig. 10. System proposed by López *et al.*

$$\phi(x, y) = \tan^{-1} \left[-\frac{I_2 - I_4}{I_1 - I_3} \right] \quad (6)$$

3.b. Hybrid Phase-shifting

These techniques can be generated using a combination of binary fringes, color-coded discrete fringes, sinusoidal patterns, and phase-shifting [30-40]. There are different variations of hybrid phase-shifting, for either a single-shot or multi-shot method.

For single-shot techniques, a color-coded fringe pattern is merged with a sinusoidal intensity pattern, creating a unique color-encoded sinusoidal pattern as shown in Fig. 11. The major advantage of this method is that it improves phase unwrapping by using the color-coded sequence, which embeds the location of each fringe within the pattern. Such encoding procedures provide better reconstructions of surfaces with large depth discontinuities. Also, knowing the location of a fringe allows a more accurate phase unwrapping by identifying the areas where a phase-step larger than 2π occurred, thus removing the ambiguity presented in traditional phase unwrapping methods. As it requires a single sinusoidal pattern and color fringes, instead of an individual pattern encoded in each color channel, the phase-shifts or steps are not necessary. The analysis is often faster than traditional phase-shifting due to the use of a single image [30-33].

Fig. 11. Discrete color fringes + phase-shifting pattern.

Wei-Hung Su [30] presents a variation of the phase-shifted pattern, where a sinusoidal fringe pattern is used to obtain the 3D shape of a surface, and the color information is used to identify the fringe order and improve phase unwrapping on discontinuous surfaces. The sinusoidal fringes and the color stripes (red, green, blue, cyan, magenta, yellow, and white) are encoded in a single image, creating a pattern similar to the one shown in Fig. 11. The stripes are grouped to simplify the phase unwrapping step, each group is formed by three adjacent fringes with a unique color order and a numeric value. These values create a code table that contains the color and numeric values of the fringes, thereby facilitating identification of fringe order. RGB planes are separated from the color image to create three binary masks for each color channel through a threshold algorithm, these masks are useful to distinguish the color fringe's distribution. And the one-dimensional Fourier transform obtains the phase distribution, ranging from $-\pi$ to π , although the calculated phase can have discontinuities of 2π phase jumps caused by surface discontinuities or insufficient sampling frequencies, thus phase unwrapping must be carried out to calculate the absolute phase. Phase unwrapping is performed pixel by pixel referencing the created code table, considering the location of the fringes to reduce those errors.

Chen *et al.* [31] also use color fringes combined with a sinusoidal pattern, proposing a hybrid analysis using wavelet transform, and triangulation to calculate the phase and height of a surface from a single image. The color fringes are encoded using the De Bruijn sequence to improve assessment of the absolute phase, while the wavelet transform retrieves the phase from the sinusoidal pattern even with varied frequencies caused by the projector-camera color distortions. Through a single image a continuous height map can be achieved, using the color fringes data to remove ambiguity presented in traditional phase unwrapping. The technique is capable of achieving the 3D image of a dynamic scene.

Fong *et al.* [32-33] present a variation of a single-shot method, using a combination of vertical color fringes and horizontal sinusoidal fringes, creating a perpendicular pattern as the one shown in Fig. 12. Color fringes are used to find the absolute phase, while the sinusoidal fringes carry the wrapped phase data of a surface. Hue classification is used to identify the edge of the fringes; to eliminate ambiguity due to the periodic pattern, phase unwrapping is performed dividing the image in small regions using the color edges.

Fig. 12. Perpendicular color-coded sinusoidal pattern.

For a multi-shot method, a color-coded fringe pattern is merged with a phase-shifted pattern, creating a series of unique color-encoded sinusoidal patterns. Phase-shifting analysis is employed to recover the

wrapped phase and an unwrapping algorithm is implemented. The advantages of these techniques is improving phase unwrapping by using a color-coded sequence, embedding the location of each fringe within the pattern, surfaces can have discontinuities larger than 2π . The difference is that more images are taken, thus requiring more processing and analysis. To estimate the phase of a surface, the three-step phase-shifting method is usually tested [34-36].

Cheng *et al.* [34] developed a different approach to the traditional phase-shifted technique, where three phase-shifted sinusoidal patterns are combined with a group of six color fringes as shown in Fig. 13. Equation (7) represents each color-coded phase-shifted pattern, where $I_1(x, y)$, $I_2(x, y)$, and $I_3(x, y)$ represent the phase-shifted patterns from Equation (1) with a phase shift of $\sigma = 2\pi/3$, and $C(x, y)$ embodies the color distribution of the fringed pattern. The three coded sinusoidal patterns are sequentially projected onto the surface. First, the six adjacent fringes are treated as one group, the color distribution is used to define the local order by finding the position of one fringe within its group. Then, the wrapped phase ϕ is calculated with Equation (8), ranging from $[0, 2\pi]$. And according to the local order the wrapped phase ϕ' range can be extended to $[0, 12\pi]$. Finally, depending on the group order, the phase unwrapping can be achieved.

For the hue identification the color model is converted to HSL, and then the hue plane is extracted with defined thresholds, through chroma identification the local and group orders are found. Some of the advantages of this technique is the rapidness to retrieve data, reconstructions of scenes with wide-ranging depths can be obtained, ambiguity is reduced, and simultaneously 3D imaging of multiple surfaces with different depths can be achieved with higher precision.

Fig. 13. Color-coded phase-shifted patterns.

$$\begin{aligned} J_1(x, y) &= C(x, y) * I_1(x, y) \\ J_2(x, y) &= C(x, y) * I_2(x, y) \\ J_3(x, y) &= C(x, y) * I_3(x, y) \end{aligned} \quad (7)$$

$$\phi(x, y) = \tan^{-1} \left[\sqrt{3} \frac{J_1 - J_3}{2J_2 - J_1 - J_3} \right] \quad (8)$$

Li. *et al.* [35] also use color information to assist phase unwrapping. Using a four-step phase-shifting technique and a color fringe pattern based in a De Bruijn sequence. The color sequence is encoded in the hue channel, while the sinusoid is encoded in the intensity channel. The wrapped phase can be retrieved from the intensity, using the four-step method. The absolute phase can be calculated from the fringe order, and later employed for correction of the unwrapped phase. Errors presented on surfaces with large discontinuities is reduced.

F. Da *et al.* [36] developed a technique that also combines the use of a sinusoidal fringe pattern and a color fringed pattern. First, a series of fringes (green, cyan, yellow, and white) are encoded into a traditional sinusoidal intensity pattern, which is projected onto a surface and a first image is taken. Sequentially, using complimentary colors a secondary fringed pattern is projected onto the surface and a second image is acquired. The wrapped phase is achieved by using Fourier transform analysis in the first image, but to accurately evaluate the unwrapped phase both images are used. The initial phase is retrieved from the sinusoidal pattern, while the color patterns improve the results. By determining the fringe order from the

first pattern, an unwrapped phase result can be achieved. However, on colorful surfaces the estimation of the fringe order can be erroneous; thus, using an additional complimentary color pattern reduces such problems on colored regions and leads to an improved phase map. According to the results, the errors on phase estimation are significantly reduced, although the major advantage is the capability to use a color pattern on a colorful surface, retrieving accurate results without affecting the color classification.

Hybrid phase-shifting techniques are not exclusively based on the use of a sinusoidal pattern, they can also be presented as a series of binary or discrete color fringes with a small phase-shift or stepping in-between [37-40]. The sequenced patterns can be projected either simultaneously for a single-shot method, as shown in Fig 14; or in sequence for a multi-shot capture mode, as shown in Fig. 15.

Fig. 14. Phase-shifted binary color fringes (single-shot).

Fig. 15. Phase-shifted binary color fringes (multi-shot).

Ayubi *et al.* [37] developed a technique encoding two binary shifted patterns onto the red and blue channels of an image, projecting a single color pattern onto a surface. Two binary patterns are created with fringes that are two pixels wide, one pattern is shifted one pixel from the other, and each is encoded onto the red and blue channels of a single color fringe pattern as shown in Fig. 16. The wrapped profile is attained from the distorted fringes, and then the phase is unwrapped and filtered to obtain the 3D surface. An additional color image can be taken to retrieve the texture of a surface and to calibrate the illumination intensity. Using a color binary pattern reduces the effects of the projector/camera non linearity, commonly presented in sinusoidal patterns.

Fig. 16. Color binary-shifted pattern.

Anguiano *et al.* [38] a multi-shot technique using a sequence of color binary fringes with a phase shift of $\pi/4$, $3\pi/4$, and $5\pi/4$ in-between them, employing a CMY color model for the projected patterns, as shown in Fig. 17. A sequence of shifted cyan, magenta, and yellow fringe patterns are projected onto a surface to acquire a single image from each one. With the three acquired images, the phase-shifting method is applied to obtain the phase map, and finally, the images from the cyan and yellow patterns are fused onto a single image. This system is capable of extracting the texture and color of a surface.

Fig. 17. Caption in 8 points size.

Chen *et al.* [39] designed a color hybrid pattern encoding sinusoidal fringes onto the red channel, and two binary fringes patterns onto the green and blue channels with a coded binary sequence. Projecting a sequence of shifted patterns, multiple color frames are acquired, and separated onto their individual color components. Sinusoidal fringes allow to obtain the wrapped phase map, while binary patterns define the fringes unique binary sequence, thus ensuring proper phase unwrapping. By using a binary sequence instead of a color sequence, the disturbance caused by the color of a surface is reduced, allowing the reconstruction of colorful surfaces with higher accuracy than those using color encoded fringes. The technique corrects the crosstalk effect, and can be applied on surfaces with sharp discontinuities.

3.c. Continuously varying

These techniques project a single pattern of spatially varying wavelength illumination, thus the color of the pattern will shift gradually throughout the surface. The color order in the pattern can be arranged from the shortest wavelength to the largest one, creating a rainbow pattern, as shown in Fig. 18. The pattern can be encoded onto a single color sequence, or on a periodic color sequence. Geng [4] previously classified these procedures into two main color patterns: rainbow 3D camera [41-43] and spatially varying color coding.

Since a single color pattern is created, a single image is captured and analyzed through the triangulation method. Representing a faster approach than phase-shifting techniques. Ambiguity is not presented since no phase-shifting or unwrapping are executed. The major disadvantages are the crosstalk, which mixes the color signals of an image, reducing the resolution and the color identification of each wavelength; and the gamma or non-linearity presented in optical devices, which distorts the projected pattern and the linearity between camera and projector. These factors complicate the separation of some colors to accurately recognize neighbouring wavelengths through the camera, and the projection of a smooth continuously varying color. These patterns are not frequently used due to the color limitations in cameras and projectors.

Fig. 18. Rainbow pattern.

The rainbow 3D camera pattern was originally proposed by Tajima and Iwakawa [41]. In their technique a white light beam was decomposed by a diffraction grating, separating the white light into its wavelengths components and thus projecting the rainbow color pattern onto a surface, as shown in Fig. 19. This method uses a monochromatic camera with color filters to obtain two images of the surface. The filters perform color separation in the images and since each wavelength is correlated to a projection angle, surface topography can be calculated using a triangulation analysis.

Geng [42] describes a similar system, using a linear variable wavelength filter instead of the grating to create the rainbow pattern and a color camera to acquire a single image. The color is detected through the color vector of each pixel in the image, the vector holds the RGB values of the pixel. Each color is then associated to a fixed projection angle given by the filter, and by triangulation analysis the surface profile is achieved. Yingming *et al.* [43] delve further into the technique, they describe how to define the parameters for the camera and projector, how to extract the hue plane by transforming the image's RGB coordinates to HSL thus defining the color planes for each wavelength, also describe the calibration procedure considering the

established parameters from the image plane and the color planes. Identification of each color is necessary to establish the projection angle, thus color crosstalk becomes a major issue. Each wavelength must be separated in the image; therefore, a rigorous calibration, model transformation, and deep analysis of the color must be carried.

Fig. 19. Rainbow 3D camera principle.

Spatially varying color coding uses a similar pattern, where the wavelength varies gradually; nonetheless, the pattern can be periodic, as seen in Fig. 20, while the rainbow pattern is not repeated throughout the projection. Geng [4] presents an example, using a periodic rainbow pattern.

Fig. 20. Spatially varying color coding.

3.d. Color-coded indexed fringes

Indexed color patterns are encoded with a specific color fringe sequence. Each color or group in the sequence is linked to a codeword that determines its individual location. Usually, a single image is acquired, thus classifying them as single-shot techniques. Indexed patterns are useful on high depth discontinuous surfaces, shadowed or colourful surfaces, since they can be segmented and analyzed in small regions, and are frequently merged with another analysis method. The codeword in the pattern can be extended by the use of more colors in the sequence.

Coded fringes patterns are encoded on a unique order, usually based on the De Bruijn sequence, creating fringes groups with non-repetitive color sequences that are linked to a codeword that allows the individual identification of each group, as shown in Fig. 21. Then through the use of phase-shifting, Fourier transform, edge detection, or color identification analysis the phase map of a surface can be retrieved. Some of the techniques that explore the use of the De Bruijn sequence are described next [31, 44-52].

Fig. 21. Color De Bruijn Sequence fringes.

As it was previously described, Chen et al. [31] combine a phase-shifting pattern and color fringes, using the De Bruijn sequence to improve assessment of the absolute phase. Each color is represented by a number, different color fringes are placed next to each other to identify the edge of each fringe without difficulty. The use of the sequence allows the recognition of the edges, using the color of the adjacent stripes; according to the corresponding edge code the absolute phase value can be extended.

Yee *et al.* [44] propose a single-shot technique, using a color sinusoidal fringes pattern encoded with the De Bruijn sequence. According to the sequence, three consecutive fringes form a unique three character code that is not repeated throughout the pattern, Fig. 22. Shows the first seven orders and their color codes. Color is used to detect the edge of each fringe, and the De Bruijn sequence simplifies the fringe order identification, which then improves phase unwrapping. The distorted fringe pattern is compared to a reference pattern through a proposed fringe analysis algorithm. Although acceptable results are reached with the technique, non-linearity of the projector affects the quality of the pattern, creating a wavy effect on the surface of the reconstruction, due to the inaccurate phase recovery.

Fig. 22. Color De Bruijn Sequence encoded on sinusoidal pattern.

Barone *et al.* [45] propose a modified technique for 3D and chromatic reconstruction using a color striped pattern and a monochromatic camera. In this method, a single color pattern is designed using the De Bruijn sequence, encoding the position of the fringe using its color value and the value from the neighbouring fringes. In the pattern six different colors were employed, and each fringe has a black gap in-between to improve edge detection, as shown in Fig. 23. The color pattern is then separated onto three binary images using the RGB planes, and their corresponding negative images are attained; the binary images are useful to define the codeword. Then, six individual patterns are projected sequentially onto a surface, a monochromatic camera acquires the images of the projected patterns. By identifying the order and edges of the fringes, the surfaces phase can be unwrapped; through triangulation the 3D surface can be retrieved. A color reconstruction is achieved through the projection of three monochromatic CMY images. This procedure reduces the number of required images, compared to phase-shifting techniques, it also achieves the 3D reconstruction including the chromatic data from the surface, and color surfaces can be tested by using the CMY color model diminishing the effects of ambient lighting.

Fig. 23. Color-coded fringes.

Zhang *et al.* [46] use color fringes encoded with the De Bruijn sequence to reduce the correspondence problem. Through triangulation analysis the topography of a surface is retrieved and the data used for triangulation is encoded in the transitions between colors. Reconstructions can be achieved through a single image for dynamic surfaces, or a multi-shot technique can be used to increase the accuracy. A 3D image can be achieved even on color surfaces, but dark areas provoke holes on the reconstruction. Crosstalk was taken into account, but improvements can be made to reduce the effects.

Fechteler *et al.* [47] developed a single-shot method with a striped pattern based on the De Bruijn sequence. To facilitate stripe detection all stripes (red, green, blue, cyan, magenta, yellow, and white) have a black space in-between, also consecutive stripes vary at least two color channels to achieve high contrast colors. The technique is used for 3D imaging of a human face; therefore, the emphasis of the proposed system is to improve the classification of the color stripes, creating a system robust to environment light, skin color, and color crosstalk.

Other authors such as: Li *et al.* [35], Pages *et al.* [48], Fernandez *et al.* [49], Chen *et al.* [50] and Zhang *et al.* [51, 52] also encode the De Bruijn sequence on color fringes, creating unique sequences in the pattern.

Some techniques encode a different sequence or codeword onto the pattern based on its color, not necessarily using the De Bruijn sequence [30, 32-34, 53-55]. Fig. 24 shows an example of color indexed fringes.

Fig. 24. Color indexed fringes.

Wei-Hung Su [30] uses a single color fringe pattern based on the combination of sinusoidal fringes and a set of color encoded stripes (red, green, blue, cyan, magenta, yellow, and white). Three adjacent fringes build one unique group with a unique color order that simplify phase unwrapping, each group is represented by a numeric value. A code table contains the fringe's color and numeric values facilitating the order identification even on surfaces with pronounced discontinuities. Fong *et al.* [32-33] and Cheng *et al.* [34] present the use of color fringes to improve the absolute phase retrieval. Six adjacent color fringes are treated as one group, and according to the order the wrapped phase range can be extended. Fong *et al.* [32-33] combine horizontal color fringes and vertical sinusoidal fringes, creating a tessellated pattern. The technique explores the use of color fringes to retrieve the absolute phase, while the sinusoidal fringes carry the wrapped phase data of a surface. Through color classification the edges can be detected, and phase discontinuities can be reduced extending the unwrapped phase. A phase correction can be encoded onto the order of the fringes.

Cheng *et al.* [53] describe a pattern in red, green, blue, cyan, magenta, yellow, and white. Six color fringes, each represented by a numeric value, are part of one group separated by a white stripe. Through permutation the order of the fringes in all sets is changed, creating a unique code for each. An angle θ_c is assigned to every stripe depending on the index of the color group and the stripe number, as shown in Fig. 25. The 3D coordinates of a surface can be retrieved through triangulation analysis, considering the projection and stripe angles. According to the results, the technique improved the resolution of the system compared to using the De Bruijn sequence. Calibration must be implemented to identify all stripes, thus crosstalk must be corrected to achieve accurate results establishing an angle for each fringe. Although it reaches higher resolution than other procedures, it's limited by the number of stripes in each group, if the test object is smaller than seven color fringes it is impossible to achieve a 3D reconstruction.

Fig. 25. Stripe angle for indexed pattern.

Je *et al.* [54] studied the importance of selecting the colors of a pattern. Having small distances between them can lead to noise and nonlinearity, while high-contrast improves the identification of each stripe but reduces the number of colors that can be displayed. Using a combination of color stripes they describe two methods using one and two shots. In the single-shot mode, consecutive stripes (red, green, and blue) have different colors, and adjacent groups have different color orders. In the two-shot mode, only green and blue stripes are present, since they have less crosstalk. While the one-shot capture reduces the processing time and ambiguities by maximizing color distances, the two-shot is insensitive to color surfaces, ambient lighting, and non-linearity.

Boyer *et al.* [55] describe one of the first systems to use color-coded indexed fringes as a single-shot technique. In their work, a set of red, green, blue, and white stripes are separated by black spaces. Through peak detection analysis a sequence of the color fringes is established from the one captured through the

camera's RGB channels. The color signals were filtered to remove variations, and then each stripe was identified and indexed. Comparing the projected and detected sequences, a horizontal displacement of the fringes can be calculated, and then used in triangulation to convert the information to 3D data. The authors proved that through a single image a full field reconstruction could be achieved.

3.e. Indexed array color patterns

Indexed color patterns are similar to coded fringes. Each element in the pattern is linked to a codeword that determines its individual location, just as the fringe order in coded fringes. A single image is acquired, categorizing them as single-shot techniques. Depending on the projected pattern they can be further classified into two groups: grid pattern and tessellated patterns.

These techniques encode a two dimensional array of grids [56-59], tessellated dots, or any geometrical shape [60-69], merging the use of color data. Each individual element is identified, spatial coding schemes assign a unique codeword to each pattern feature, and an analysis technique is implemented to acquire the topography. Since any shape can be implemented, array patterns have a wide range variety; encoding data through color, location, or shape in the elements. They can achieve 3D imaging from one shot with a wider scene and higher resolution, depending on the size of the elements.

Nonetheless, it can also be challenging to identify each element of the projected array, and color crosstalk can be seen on neighbouring elements, complicating the decoding of the pattern. All indexed patterns have a correspondence problem, which is presented when matching the same point between the projected and acquired images. Although, the correspondence issue is diminished by the use of structured light, reducing the problem compared to a stereovision system. One of the major issues with these techniques is that due to the spacing between each element, sparse data of a surface can be retrieved, leaving possible areas where no data is obtainable; thus the accuracy of the reconstruction depends on the number of elements and spacing in between them.

Grid patterns have been explored by different researchers [56-59]. A grid is created through the projection of vertical and horizontal stripes using color. These techniques can be sufficiently accurate, and line detection can be simpler and faster than shape detection, making them the simplest of indexed array patterns. Nonetheless, sparse reconstructions are obtained when using fewer grid lines or wide spacing in-between. Fig. 26 contains a grid pattern in two colors.

Fig. 26. Color grid pattern.

Kawasaki *et al.* [56] proposed a grid pattern composed of vertical red lines with regular intervals, and horizontal blue lines with irregular intervals, as shown in Fig. 27. Placing horizontal lines at uneven intervals, makes the technique more robust since it is less affected by the texture, or shape of a surface. Correspondence is achieved by comparing the points of intersection between vertical and horizontal lines in the calibrated pattern and acquired image. Locating the peak crossing grid points, and the distance from neighbouring points can retrieve the position. The technique can recover the 3D surface without encoding information onto the pattern, instead only using the intersection points on the grid pattern. Also, it can be used on high resolution shapes, allowing the lines to be as dense or thin as necessary. According to the results the technique is not affected by the distortion of the pattern or surface texture. Ulusoy *et al.* [57] proposed a modification using the De Bruijn sequence. A grid pattern formed by horizontal blue lines, and vertical red lines is projected. Through color thresholding the horizontal and vertical lines can be

differentiated, and grid points can be located. Correct correspondence between the computed grid points and projected grid reference is almost unreachable due to system imperfections. To improve correspondence, the technique is modified so the spacing between horizontal and vertical lines is encoded using the De Bruijn sequence. Through triangulation the 3D surface can be retrieved. Authors demonstrate that using an encoded grid pattern increases the robustness of the reconstruction compared to a regular grid pattern. Since the method is not affected by the texture or color of a surface, it can be used on irregular surfaces.

Fig. 27. Color grid pattern with irregular intervals.

Sagawa *et al.* [58] studied a periodic grid, where the lines were encoded by the De Bruijn sequence. Color codes and sequence for each line is decoded. A phase value is interpolated to regions that are not covered by the grid. The proposed technique also reduces phase ambiguity. Using the phase-unwrapping algorithm a continuous phase map was retrieved. Their approach seeks to reduce the major issue of sparse data, even when fewer gridlines or intersection points are present. To do so, pixels from neighbouring regions are used for a denser reconstruction.

Salvi *et al.* [59] used a grid pattern composed of vertical and horizontal lines. Six colors were used as coding elements, assuring that the color sequence from a slit and its two neighbours appear only once. Horizontal lines are encoded in red, green, and blue; while vertical lines are in cyan, magenta, and yellow. These colors improve accurate segmentation based on the hue and saturation components. 3D data is retrieved from the cross-points of the pattern, through color codification the coordinates of each cross-point in the image plane and projector plane are determined.

Tessellated patterns are 2D arrays composed of geometrical shapes, where each element has encoded data. The codeword can be retrieved by identifying all elements or intersection points, and their color. As with grids, variant patterns can be created using different geometric shapes and colors. These techniques retrieve 3D reconstructions with higher accuracy than grids, since the spacing in between can be smaller and placing can be denser. Although, identifying each element can be complex thus finding the codeword can lead to major processing difficulties. Color crosstalk can be present on such patterns, in the junctions of elements. Fig. 28 shows a tessellated pattern in color, with black spacing in-between.

Fig. 28. Tessellated pattern.

Song *et al.* [60] used rhombic shapes and four colors to encode the pattern, as shown in Fig. 29. The points of adjacent elements were defined as the features. Lin *et al.* [61] modified the previous technique, embedding onto some of the elements in the rhombic pattern a small white geometrical shape to avoid the use of more colors, extending the elements to eight. Through color and geometric decoding methods, a codeword can be linked to each grid point. To decode each feature point, color identification is carried in the adjacent elements. Their work highlights that using more colors in a pattern complicates color

identification, but reduces the size of the coding window; while using less simplifies the identification, but increases the coding window. The advantage of using a rhombic shape is that it allows the use of same color on adjacent elements, and the grid points can be localized using the symmetry of the shape instead of color segmentation. Once the grid points are found, color and geometrical features are used in the decoding process to find the codeword; decoding the shape identifies embedded or solid elements. For color decoding the image is converted to a HSV color model. A high accuracy was reached with the proposed technique.

Fig. 29. Tessellated rhombic pattern.

Chen *et al.* [62] describe a tessellated pattern, using seven different colors as shown in Fig. 30a. White improves color identification, separating two consecutive colors. A unique codeword can be decoded from the hue of an element and its four adjacent neighbours. The coordinates of an element in the image can be calculated from the codeword, and are correspondent to real coordinates. The technique allows the reconstruction of dynamic surfaces through a single image, without compromising accuracy. Desjardins *et al.* [63] use a pattern formed by colored squares (red, green, and blue) separated by a black gap to facilitate segmentation, as shown in Fig 30b. The color code of a sub region is not repeated throughout the pattern due to an iterative code generating algorithm. The color regions of interest are segmented from the black areas. Then, a labeling algorithm groups pixels, and a grouping evaluation is performed. Small regions of neighboring 3x3 pixels create a color code from the acquired image, and are then compared to the original code. Erroneous codes can be detected even when the projection/acquisition is of high quality, which is a drawback of these techniques. A code-correction is implemented, and erroneous codes are removed from the results; allowing the removal of faulty or non-relevant data, while holding high-density data. Due to the use of multiple cameras, the system calibration between cameras and projector can be waived, although a calibration for the cameras is performed. An additional image can be taken without the projector to retrieve the texture of the surface. Spoelder *et al.* [64] proposed a checkerboard pattern using two different colors for encoding, and black to separate the data. The pattern encodes three sets of data: geometrical, color, and the codeword. The geometrical and color information retrieve data for 3D imaging, while the codeword validates the results.

Fig. 30. Tessellated pattern with: a) seven colors, and b) black gap between elements.

Adán *et al.* [65-66] created a pattern of color spots (red, green, blue, cyan, magenta, yellow, and white), as shown in Fig. 31. The codeword was defined by the color feature of an element and its six surrounding colors. The pattern can be disordered, and elements of the codeword can be repeated. Through their work a tracking method is presented to allow the following of the feature points of a pattern throughout a moving scenario, reaching the 3D coordinates of each point in a moving object. Morano *et al.* [67] also describe a pattern of color dots (red, green, and blue), where a letter is encoded to each. The neighboring eight elements create a nine word letter that indexes the projection coordinates. The paper addresses the correspondence problem and presents a method to simplify the matching of the projection and image points. An advantage of using tessellated patterns instead of fringes patterns, is that they can be used on

non-coplanar surfaces and the number of colors required for encoding is reduced. Davies *et al.* [68] also describe a spots pattern (cyan, magenta, and yellow), although a hexagonally tessellated array is presented. Creating a codeword by the color of a spot and its surrounding neighbours to determine the position of the element in the projected array. On surfaces with different depths some elements of a pattern can be distorted or incomplete, complicating the correct identification of each. To reduce these effects the authors study not only the location or color of an element, but determine the orientation of each. Through the proposed analysis the orientation can be determined, and then used to rescale the element to be able to correctly detect the rest. Since a single image is acquired, all the previous techniques can be used when testing dynamic surfaces.

Fig. 31. Tessellated dot pattern.

Albitar *et al.* [69] propose an indexed pattern using monochromatic light. A green laser beam is shaped into the pattern by a diffractive optical element. Since a single color is used, an alphabet of three geometrical symbols is created, and unique windows of nine elements are analyzed. The segmentation algorithm doesn't require the identification of color, since monochromatic light is employed. First, the contour of the symbols is detected, tagging them as a: circle, disc or line. Then, based on the orientation of the line, the neighbouring elements of each symbol are found. Once the neighbours of an element are found, a codeword is set for each window. The proposed technique can be implemented on dynamic surfaces, and can be a compact system such as an endoscopic tool. A green laser at different wavelengths was used after studying the reflectance of an organ in the body.

3.f. Color identification

Color classification explores the direct identification of color features in a pattern. Once the features are classified the results can be employed on other techniques, such as color phase-shifting to determine the fringe order or indexed array to find a codeword. Not many methods implement color identification due to the complexity of accurately identifying and classifying color features, since these require a rigorous calibration to assure that the projected and acquired color are fairly similar to the established color value. These procedures often recommend the use of the HSL color model instead of RGB, since the hue plane provides greater information about the wavelength disregarding the intensity, or lightness of the color. Fig. 32 shows an example of color identification; extracting the color vector which holds the hue, saturation, and luminance values from a pixel or segment in the image, then based primarily on the hue classifies the analyzed region as blue.

Color identification or classification can be used as an auxiliary method on various color-coded structured light techniques such as hybrid phase-shifting, color-coded indexed fringes, or color indexed array.

Considering that location coordinates from the original pattern are encoded as a codeword using color information; decoding the color vector of a fringe or element in a pattern on a surface increases the data that can be retrieved. Although many authors describe the use of color identification, few are focused on employing it as the primary analysis method to obtain the topography.

Fig. 32. Color classification.

Zhang *et al.* [51-52] researched color identification, using De Bruijn color-coded fringes. Decoding color data can be executed through three steps: detection, identification, and correspondence. The first step, code detection searches for color features in the acquired image through peak detection on multi slit techniques, border detection on fringes, line detection on slit methods, and corner detection on mosaic patterns. Color identification groups similar data as part of one group and a code label is assigned. At last, correspondence gets the code sequence for each line and finds a matching group for the acquired color pattern. To evaluate different methods, special attention is brought to two aspects: color feature selection and the clustering algorithm. In their work, different color models were employed to select and tag different features: each model was evaluated by the precision and separability measurement, meaning how different the color classes are. According to the results, the best identification is achieved with the regularized RGB and normalized RGB color models.

On color binary + phase-shifting techniques color identification can be employed to find the fringe order, and recover the unwrapped phase without ambiguous results. Cheng *et al.* [31] convert the image model from RGB to HSL, then the hue plane is extracted, and with set thresholds each color can be identified. Fong *et al.* [32-33] use a Bayesian filter to identify each color. F. Da *et al.* [36] transform the color planes to binary intensities, then segmentation is carried through a threshold algorithm, and to reduce the effects of colourful surfaces complimentary color fringes are projected.

In the rainbow 3D camera technique [41-43], color identification is employed to establish the color planes for each wavelength, and the associated projection angle.

Color-coded fringes patterns frequently explore the use of color classification either to identify a sequence of fringes and retrieve its sequence [44-46], or to find the codeword associated to an element or a window of elements [60-64].

Tornero *et al.* [70] describe a new approach where color identification is used as the primary analysis method, without the need of any additional analysis. A color pattern is described using color fringes in red, green, blue, cyan, magenta, and yellow. With an orthogonal setup each fringe is encoded with a height value, as shown in Fig. 33. The color vector of all pixels is obtained, and a color tag and height value are assigned to each. 3D imaging is achieved through the height values.

Fig. 33. Color classification.

3.g. Multiple color-coded patterns

Structured light techniques are limited by the projection area, due to projector specifications the pattern can only be projected onto a constrained region, and some sections of the surface can be shaded by discontinuous surfaces. To ensure that the light pattern is projected onto the entire test surface and that minimum shadows are present, multiple projectors are employed, as seen in Fig. 34. Although the use of multiple projectors can raise the cost of the system, it can considerably improve the results if large or discontinuous surfaces are tested. Using multiple projections modifies the traditional analysis since the overlapping of light patterns must be considered [23, 58, 71].

The greatest advantages of using multiple projectors is the ability to reduce shadows in the acquired image caused by occlusions of the system configuration, the use of multiple patterns, and an extensive projection area. Although they may improve the projection on a 3D imaging system, these techniques can increase crosstalk on an image so they require the implementation of a corresponding or matching algorithm, complicating the analysis and calibration. The system must be calibrated so all the projections have the same parameters in color, brightness, and contrast; having a similar resolution and characteristics on all projector units. The projection angles must be measured, and the analysis method must be adapted to the use of multiple projectors. Color crosstalk is present due to the overlapping of multiple projections, thus an algorithm is necessary to accurately separate or differentiate one pattern from the other.

Fig. 34. Multiple color-coded pattern projection system.

Skydan *et al.* [23] describe a color technique using multiple projectors placed on different angles. A red phase-shifted pattern is projected from one angle measured from the camera's optical axis, while simultaneously a blue pattern is projected from another angle. Since both projectors have different light projection fields, a wider scene of the surface can be studied. A single color image is taken, and then decomposed on its individual planes. The phase can be attained through Fourier transform analysis, combining the phase maps retrieved from each color pattern, the topography of a surface is achieved. The system can be used even when a surface has large depth discontinuities, with a simultaneous projection the pattern can be lighted onto a larger section of the surface. The authors were able to retrieve 3D data from isolated sections of the surface, reducing large phase steps on discontinuous or isolated surfaces.

Sagawa *et al.* [58] present an alternative using multiple projectors. One projector casts horizontal lines and the other vertical lines, forming a grid pattern on the surface. The analysis reviews how to establish the correspondence between camera and projectors, the technique formulations presented can be extended to the use of three or more projectors. Higher resolution was reached with the use of three projectors.

Je *et al.* [71] present a study of using simultaneously multiple projectors, and how color patterns are affected by their superposition. Their method is based on the projection of multiple striped patterns with different orientation, stripes are coded using RGB colors since they have the largest chroma separation. After separating the images based on their orientation cue, the superimposed pattern can be divided onto two patterns. Then, through the analysis of color, the stripes can be decoded and classified in different groups or classes. The 3D image of dynamic surfaces is achieved, using two cameras and two projectors. The described technique overcomes the interference presented on systems based on multiple projections, through the use of an orientation cue both patterns can be retrieved, and then based on the color analysis

the patterns originally projected can be found. Although it has trouble on colourful surfaces, which interfere with the projected color and thus color segmentation performance decays.

4. Conclusions

Structured light techniques are widely recognized and researched in 3D imaging, due to their rapidness acquiring broad surface data in a single frame, and the measurement accuracy provided. Extensive research has shown a wide range of methods that can be broadly classified as: sequential projection, continuous varying, and stripe indexing.

Phase-shifting is a renowned sequential projection technique, based on projecting a series of sinusoidal fringes with a small phase-shift in-between. Although it provides high accuracy, ambiguity is presented on discontinuous surfaces, and the reconstruction time increases with the quantity of phase-shifts performed.

The use of color on structured light has often been researched, providing new techniques that encode additional data onto a pattern through color-coding to reduce ambiguity and reconstruction time. A new classification exclusively for color-coded methods is proposed, according to the encoding of the projection and the acquisition type, all patterns can be classified as phase-shifting, binary + phase-shifting, continuously varying, indexed fringes, indexed arrays, color identification, and multiple color-coded patterns.

Color phase-shifting techniques encode through the color channels of a camera a set of three sinusoidal fringes with a small phase-shift in-between, through traditional phase-shifting analysis the wrapped phase of a surface can be retrieved and then unwrapped to achieve the 3D image. According to the number of acquired images, all methods can be subdivided into single-shot and multi-shot. Various authors explore color phase-shifting, since it improves the intensity phase-shifting method, reducing ambiguity due to color encoding, and acquisition time due to the projection of a single pattern.

Hybrid phase-shifting color techniques merge the use of a sinusoidal or phase-shifted pattern and a discrete or binary fringes pattern. These methods can also be subdivided into single-shot and multi-shot. For multi-shot mode, a set of three individual binary color fringes patterns with a phase-shift in-between can be projected sequentially onto a surface, thus requiring the acquisition of multiple images. For single-shot a single pattern is created combining a sinusoidal and a discrete color fringes pattern. A set of three individual binary color fringes patterns with a phase-shift in-between can also be encoded onto a single image through the color channels. Through a combination of border detection and phase-shifting analysis the phase of a surface is retrieved. These techniques are used due to their ability to reduce color crosstalk, they also improve phase unwrapping and reduce ambiguity by extending the phase through the use of color-coded fringes.

Continuously varying color are single-shot methods, based on the projection of a gradually changing wavelength throughout the pattern. A single rainbow pattern or a periodic sequence repeated throughout the pattern can be projected. Although some authors have described the use of the technique, it's not employed often due to the difficulty of accurately projecting a pattern with small color variations in-between, also it's hard to differentiate such variations through a camera, color crosstalk is heavily present on these patterns.

Color-coded indexed fringes encode a sequence of fringes with a codeword, creating a unique code for a group of fringes. Finding the codeword for each group provides additional data that can be used on the analysis, such as the location of the fringe. The De Bruijn sequence is often encoded onto a pattern since it provides a unique code for a set of fringes, although it is shown that some authors use a different sequence for encoding. The effects of color surfaces and ambient lighting is reduced, these methods can also be merged with phase-shifting as an improvement for phase retrieval of surfaces with large discontinuities.

Indexed array patterns are created encoding a bi-dimensional array of geometrical elements and color, creating a gridline or a tessellated pattern of different shapes. A codeword can be embedded onto the color elements or the crossing points of the pattern. Finding the code of the crossing points in the pattern determines the location of each element, which can be converted onto 3D coordinates. These techniques are useful for dynamic surfaces, they usually present higher resolutions based on the distance and size of the elements in the array, and data is encoded onto a pattern through color, location, or shape in the elements.

Color identification is often implemented as a complementary analysis method, merging with other such as: phase-shifting, color-coded indexed fringes, and indexed array patterns. These techniques improve the results by detecting the color features of an element in a pattern. On color hybrid phase-shifting they are implemented to decode the pattern and determine the location or group of fringes that's being analyzed, then according to the group the phase of the pattern can be extended or corrected. On indexed fringes and array patterns, color classification can also be used to find the elements codeword used to achieve the 3D image. A new technique proposes the use of color identification to retrieve the topography by embedding a height value to each color.

Multiple color-coded patterns improve the reconstruction area of a system by using multiple projectors with different light projection fields. Thus, reducing the unreachable areas of a surface, shadows presented in discontinuous objects, and improving resolution. Analysis of two projected patterns can become complicated, since the overlapping occurs it has to be solved by separating each pattern to be individually analyzed, and then the results can be combined on a single reconstruction. These techniques must be strictly calibrated to establish the correspondence between the multiple projectors and camera.

Color coded techniques are widely recognized in 3D imaging due to their variety, robustness, and capability to encode more data onto a single pattern through the color planes of an image. Single-shot capture modes are ideal for dynamic scenes, since they provide through one frame the data of the surface and different analysis methods can be implemented. Multi-shot capture modes increase the precision of the 3D image since they are able to retrieve more surface data, while the use of color allows to reduce some of the limitations of other techniques. The use of color infers a high-quality projector and camera must be used to approach the color images as near as possible to the real hue, color calibration and transformations have to be address to reduce the effects of crosstalk and thus achieve better results.

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