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High dynamic range 3D measurement based on structured light: A review

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Abstract: Structured light method is one of the best methods for automated 3D measurement in industrial production due to its stability and speed. However, when the surface of industrial parts has high dynamic range (HDR) areas, e.g. rust, oil stains, or shiny surfaces, phase calculation errors may happen due to low modulation and pixel over-saturation in the image, making it difficult to obtain accurate 3D data. This paper classifies and summarizes the existing high dynamic range structured light 3D measurement technologies, compares the advantages and analyzes the future development trends. The existing methods are classified into multiple measurement fusion (MMF) and single best measurement (SBM) based on the measurement principle. Then, the advantages of the various methods in the two categories are discussed in detail, and the applicable scenarios are analyzed. Finally, the development trend of high dynamic range 3D measurement based on structed light is proposed.

Keywords: High dynamic range; 3D measurement; Structured light; Phase calculation; Shiny surface

1. Introduction

Structured light 3D measurement is a method widely used in many aspects of industrial production due to its good stability and measurement speed[1-5]. It can be applied in procedures including defect detection, waste classification, and parameter optimization[6-9]. However, when the surface of industrial parts has high dynamic range (HDR) areas such as rust, oil stains, shiny surfaces, phase calculation errors may occur due to low modulation and pixel over-saturation in the image. As a consequence, it might be difficult to obtain accurate 3D data. Therefore, obtaining precise 3D data of a high dynamic range surface remains something to be studied.

The ordinary method to overcome this issue can be divided into three different types. 1) Contact measurement[10,11] uses specialized equipment for high dynamic range areas; for example coordinate measuring machines (CMM) and light pens. The measurement accuracy is high, but the measurement speed is slow, so it is still difficult to obtain three-dimensional shape and size data. 2) Powder spraying can also be used to create a thin layer of powder on the surface of the workpiece to make the surface appear diffuse reflection[12,13]. The accuracy of 3D data, in this case, depends on the thickness of the powder, and it may damage the workpiece. 3) Using a multiple viewpoint approach[14-17], 3D data can be reconstructed and merged from the viewpoints to supplement the dark and shiny parts. The method is simple to operate, but increases the amount of data that has to be processed, so its effects depend on the quality of the planning viewpoint. These three methods can achieve HDR 3D measurement in some aspects, but might not be completely accurate and efficient.

Many researchers have studied this problem and proposed different methods that can be mainly classified into Multiple Measurement Fusion (MMF) and Single Best Measurement (SBM).

1) The MMF-based methods attempt to overcome the aforementioned issues by obtaining images of the same viewpoint with different parameters; e. g. exposure, projection intensity, and color channel. In theory, MMF method could solve such issues by setting appropriate parameters for different reflection regions. However, how to set parameters that can satisfy all areas remains a challenge.

2) The methods based on SBM have the potential to fix this matter through single measurement that refers to the best projection pattern, additional equipment, or image enhancement with deep learning. The principle of SBM is very efficient, but its current actual effect is not as satisfactory as MMF. Therefore, the most widely recognized method is a multiple exposure fusion method applied to MMF, since its operation is simple and it doesn't require extra equipment.

Considering the different principles and features of the aforementioned methods, it is crucial to analyze and discuss their practical applicability. By studying the methods, it is possible not only to help novices to get started quickly, but also help those in need to choose the most suitable method for different measurement needs.

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For this reason, this paper comprehensively reviews the methods from both principles and their applicability. The general camera-imaging model for structured light 3D measurement is introduced in section 2 and the MMF-based methods usually used in HDR 3D measurement are introduced in section 3. In section 4 the SBM-based methods are introduced and section 5 discusses the future research directions of HDR 3D measurement based on structured light, presenting a conclusion to what has been proposed in this study.

2. Camera-imaging model

When using structured light technology for measurement, the projector displays a set of fringe patterns on the surface of the object of study, while the cameras simultaneously capture images[18-20]. Due to a change on the surface geometry of the measured object, the grating fringe pattern taken by the camera gets deformed. Then, the phase calculation, phase expansion, and stereo matching are carried out according to the algorithm. Finally, a three-dimensional point cloud is reconstructed using the principle of triangulation.

In structured light 3D measurement, as shown in Fig. 1, the camera-imaging model can be expressed as

$$I = \alpha t(\beta I^{a_1} + \beta I^p + I^{a_2}) + \mu \tag{1}$$

where α is the sensitivity coefficient of the camera, t is the exposure of the camera, β represents the reflection coefficient of the measured object, I^{a_1} stands for the ambient light shining on the measured object, I^p is the light intensity of the projector, I^{a_2} is the ambient light directly entering the camera, and μ represents the noise error of the camera. Considering that the projected image is a series of other sinusoidal fringe images with constant phase-shifting amount, the grayscale distribution of the image can be expressed by simplifying and modifying the aforementioned formula as:

$$I_n(x,y) = A(x,y) + B(x,y)\cos(\phi(x,y) + \delta_n) \quad n = 1,2,...,N \tag{2}$$

where $A(x,y)$ is the average intensity, $B(x,y)$ is the modulation intensity, $\phi(x,y)$ represents the phase to be solved for, and δ_k is the phase shift. $\delta_n = 2\pi(n-1)/N$ represents the phase-shifting amount. The key for structured light technology is to recover the phase $\phi(x,y)$ from the sequence of fringe images acquired by the camera to achieve the corresponding point matching, and to reconstruct the point cloud data. $\phi(x,y)$ and $B(x,y)$ can be solved by

$$\phi(x,y) = \text{-arctan}\left(\frac{\sum_{n=1}^{N} I_n(x,y)\sin(\delta_n)}{\sum_{n=1}^{N} I_n(x,y)\cos(\delta_n)}\right) \tag{3}$$

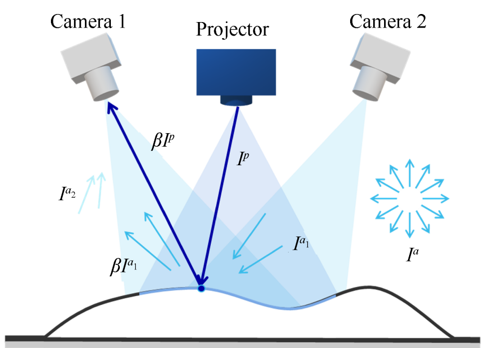

Fig. 1 Camera imaging model.

$$\begin{cases} B(x,y) = \dfrac{2\sqrt{T_1 + T_2}}{N} \\ T_1 = \left[\sum_{n=1}^{N} I_n(x,y)\sin(\delta_n)\right]^2 \\ T_2 = \left[\sum_{n=1}^{N} I_n(x,y)\cos(\delta_n)\right]^2 \end{cases} \tag{4}$$

According to Eqs.(2)-(4), it is possible to conclude that the accuracy of the phase calculation depends on the relative accuracy of the image gray value and the brightness value of the actual projection.

However, due to limited camera equipment, the normally used image intensity range $I_{cam} \in [0,255]$ cannot be expressed with its real intensity. If the surface of the industrial part has high dynamic range (HDR) areas (e.g. rust, oil stains, shiny sections) the gray value of the corresponding pixel in the image is not accurately represented, causing a phase calculation error.

3. Multiple measurement fusion

The purpose of MMF-based methods is to replace the over-saturated or low-modulation area with a suitable range area in the image obtained by different parameters. The MMF-based methods are mainly used in HDR 3D measurement procedures and count on important features like multiple exposure fusion, and multiple projection fusion.

3.1 Multiple exposure fusion

Multiple exposure fusion technology refers to the blending of images collected under different exposure times with the same viewpoint into one image. The procedure is conducted to avoid image saturation and achieve higher modulation intensity. Taking this principle into consideration, Zhang and Yau[21] proposed a high dynamic range scanning technique based on multiple exposures. First, a series of fringe image sequences with different exposures from high to low are obtained. Then, as shown in Fig. 2, the pixel value of the fusion image is selected based on the idea that all pixels occupying the same position in the fringe image with the same frequency sequence are not saturated and are the most intense ones. This method is easy to operate and has satisfactory effects since the influence of ambient light on the phase-shifting method is not much. However, in the experiment exposures were chosen subjectively, which required a lot of photos to be taken (e.g. 23 different exposures for a vase). Therefore, it remains necessary to create a method to automatically select proper exposures that consider both effect and efficiency.

3.1.1. Auto-exposure

Some researchers have already tried to find a way to automatically determine exposures for HDR 3D measurement. For instance, Jiang et al.[22] proposed a method to automatically select exposures and projected fringe intensity. All possible parameter candidates in ascending order are set by the principle of maximizing projection intensity and minimizing exposure. Then, the uniformly illuminated beams are projected to calculate the masks of valid parameters by the criterion of maximum modulation instead of maximum and non-saturation criterion of image intensity. This method is robust and insensitive to ambient light; this is why it can be used to increase measurement automation. However, this method requires far more images than the traditional method, and the effect depends on the initial candidate points that cannot set automatically. To solve this issue, Feng et al.[23] proposed an automatic generation algorithm

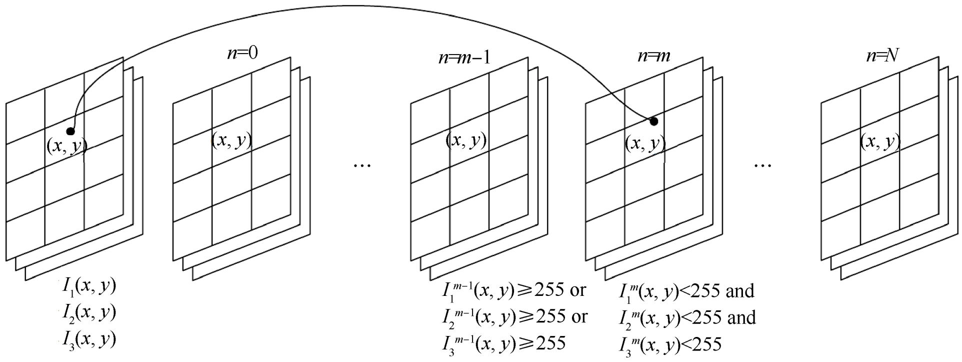

Fig. 2 Multiple exposure fusion proposed by Zhang and Yau[21].

of exposures based on a reflectivity histogram. As shown in Fig. 3, the method divides the imaging area into several clusters with a smaller range according to the reflectance histogram distribution. It calculates the exposures according to the value of the significant valley on the right side of each cluster to be able to completely cover each one. This process can automatically generate exposures to improve automation performance. However, this histogram clustering distribution, which is designed to predict exposures, might not be applicable to objects with insignificant reflectance category distribution, as it can easily produce blocking effects.

Rao and Da[24] proposed an automatic multi-exposure FPP based technique that could predict exposures according to the modulation of the histogram. The idea is to divide the image into several areas by modulation, to calculate the exposure that makes the modulation of every area larger than the set threshold. This method can automatically predict the valid exposures by modulating the gray value, and the number of exposures tends to be 5 because of its threshold.

Zhang[25] presented a strategy that determines the optimal exposure through an image under low exposure with a uniform white image projected that can find the next exposure in sequence. The idea is to select the optimal time that makes the gray intensity of the most reflective area reach its maximum and non-saturation with the pre-calibration of camera noise first. The following step is to select the next exposure by the principle of making the last minimum value become the maximum value of this exposure until the exposure exceeds the limit or intensity of all areas and makes it greater than the set minimum value. The essence of this method is to calculate the exposure according to the set intensity interval, which can be replaced by a histogram or by the same number pixel. The proposed method is biased to the overall bright area of the scene, and the effect on darker areas is not evident. Its actual effect depends on the set threshold and pre-calibration precision.

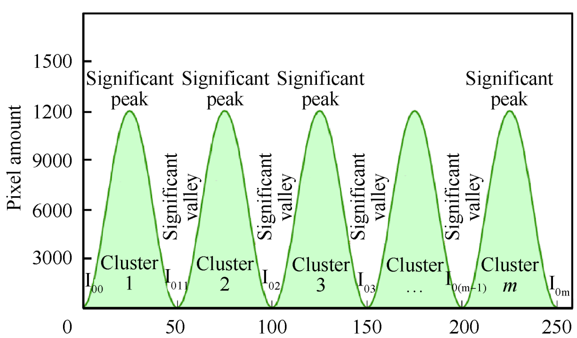

Fig. 3 Example of histogram of I0[23].

3.1.2. Measurement acceleration

Some researchers have tried to increase the measurement speed as a way to reduce the efficiency loss caused by multiple measurements. Liu et al.[26] proposed a method to achieve HDR 3D measurement by combining a binocular camera and two binocular camera-projector system based on multiple exposures. The method achieved more satisfactory results than traditional ones by reconstructing some areas that only over-saturated or presented low-modulation in one camera. However, the accuracy of reconstruction results also depends on the camera-projector calibration, which tends drift due to heating.

Zhao et al.[27] suggested a rapid HDR 3D measurement method that could improve the projecting speed and intensity. The outcomes of the technique showed that the new projector could reach a maximum frame rate of 700Hz by high-frame signal transmission mode LVDS (Low-voltage Differential Signal), and that the range of light intensity can vary at least 9 times. In the experiment, the projector could reduce the projecting time by about 60% at 60 Hz.

Suresh et al.[28] presented a real-time HDR 3D measurement method based on the transitioning state of DMD (Digital Micromirror Device)[29]. It achieves HDR 3D measurement with high speed by binary defocusing[30] and by using two exposures in one single projection by setting precise control for both camera exposure and projection exposure, as shown in Fig. 4. The method could improve the speed, but was only able to achieve two exposures in one, which may not meet the demand of the parts involved in the process.

Based on binary defocusing and the idea of two exposures in one projection, Zhang et al.[31] suggested a method of HDR 3D measurement with a mixed phase unwrapping algorithm that could reduce phase unwrapping errors for dense fringe patterns. The technique was able to perform real-time 3D measurement for HDR scene like the model used at 28 frames per second.

Wang et al.[32]proposed another fast HDR 3D measurement based on auto-exposure and binary defocusing that was able to generate the optimal exposure interval by using two sets of pre-captured additional fringes. This vastly improves the measurement time of pre-captured to reduce time consuming by older solutions, including its like camera response function, etc.

The advantage of the multiple exposure fusion method is its simple operation and precision. For the method to work well, it is only necessary to adjust the exposure, and no additional equipment is required. Therefore, it can be considered that is has many applications, e.g. industrial sheet metal, multi-textured surface, and multicolor surface.

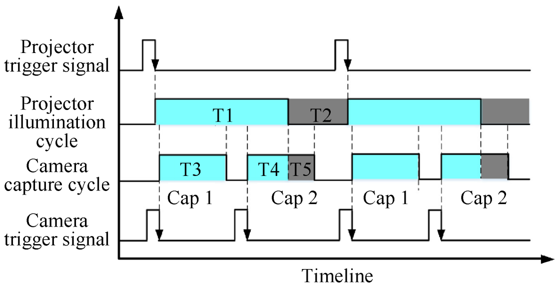

Fig. 4 Timing chart for projector and camera trigger and exposure control[28].

3.2 Multiple projection fusion

In addition to adjusting the exposure time to achieve HDR 3D measurement, another common action is to adjust the global intensity of the projector. Waddington and Kofman[33] considered adjusting the projection intensity through the maximum input gray level (MIGL) to avoid saturation. By doing this, it is possible to get the HDR image frame by frame and identify the different intensities in each. This method cannot have enough exposure range but it can be changed accordingly and used as a supplement.

Jiang et al.[22] used different projection intensities and exposures to obtain a HDR image. The error caused by the ambient light is reduced by increasing the intensity, so the range of measurement could be increased too. Waddington and Kofman[34] proposed a new way to get the HDR image by projecting different MIGL patterns. It selects the appropriate pixel by the principle of high modulation and non-saturation without changing the camera.

Sheng et al.[35] proposed a way to modify the projected image based on the last image acquired by camera. The first step is to calculate the point spread function of the over-saturated pixel, and then use a gray-scale correction function to generate the modified image. The method could effectively reduce the number of saturated points by one or two iterations that will be useful for objects with shinny surfaces.

To make the intensity selection more automatic, Zhang et al.[36] suggested a multiple projection fusion method based on the camera response model. It calculates the reflection coefficient corresponding to each pixel, and divides the area through the reflection histogram. Then, according to the pre-calibration model, the best projection intensity of every area is calculated by the upper and lower limits. The results have more analytical significance compared with the ones obtained by directly using the gray histogram to make image segmentation, it is important to highlight that the area segmentation is not automatic.

The advantage of the multiple projection fusion method is similar to the positive aspects of multiple exposure fusion, but the method didn't reach enough dynamic range. Therefore, we concluded that this method can be used as a supplement for multiple exposure fusion.

3.3 Polarization filter

The main problem of HDR 3D measurement is often the specular reflection in some areas because of the angle. Aiming to overcome this obstacle, some researchers tried to remove the specular reflected light through polarization filters to avoid over-saturation. For instance, Chen et al.[37] proposed a method of 3D measurement for translucent objects that consisted of adding two polarization filters, as shown in Fig. 5. The method was able to reduce the influence by subsurface scattering in translucent objects to avoid over-saturation. However, this causes the modulation to be low at the same time. To solve this issue, Li et al.[38] thought about a method that acquires the HDR image by multi-polarization fringe projection. It first puts a linear polarizer in front of the projector to polarize the projected image, and then obtains different images according to the pixelated polarizer array of the four states in front of the camera. The method could successfully reduce the over-saturation issue caused by the specula reflection, but the system to do so is complex. Feng et al.[23] proposed a method that combines multiple exposures and polarization filters to perform HDR 3D measurement. Because of the polarization filter, the image obtained by the camera has a low degree of modulation, so it is necessary to extend the exposure to meet the darker area.

Since the specular reflection is removed, this method is advantageous because it can be applied to shiny surfaces. But for darker areas, it tends to cause larger errors due to lower modulation.

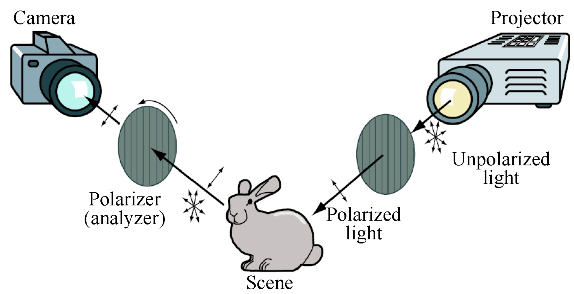

Fig. 5 System proposed by Chen et al.[37]

3.4 Other technologies

The fusion image could also be obtained by adjusting the RGB camera and some projection patterns.

Jiang et al.[39] proposed a method based on the combination of original and reverse fringe patterns. The method is based on the projection of the original fringe patterns and the 180-degree phase-shifted (or inverted) fringe patterns to calculate the phase. When the pixels of any fringe image are saturated, the ones on the reverse fringe and the corresponding formula are used to calculate the accurate phase. This method can reduce the influence of errors caused by saturation due to excessive projection fringe intensity. However, it uses different formulas to calculate the phases and cannot be expanded to four-steps shifting. Aiming to overcome this obstacle, Wang et al.[40] put forward another method that could calculate the phase with generalized phase-shifting algorithm based on all the unsaturated pixels in regular and inverse patterns. The method is able to simplify the calculation process and get better results as the experiment show.

Yin et al.[41] proposed a method able to synthesize the HDR image with color camera and calibrated attenuation ratios. It followed the idea that different channels have different quantum efficiency curves versus wavelength due to the selectivity of the filter. This new technique could be useful in industrial parts with same color, but may cause errors for objects with color textures. As shown in Fig. 6, the same group was proposed by a real-time HDR 3D measurement method after replacing grayscale cameras with RGB cameras[42]. With that, six different images were obtained by combining two exposures in one projection and three channels with different responses to single color light source in RGB camera.

Song et al.[43] put forward a method using binary pattern instead of sinusoidal pattern to achieve 3D measurement for specular objects. It first introduces an efficient means to estimate the camera re-

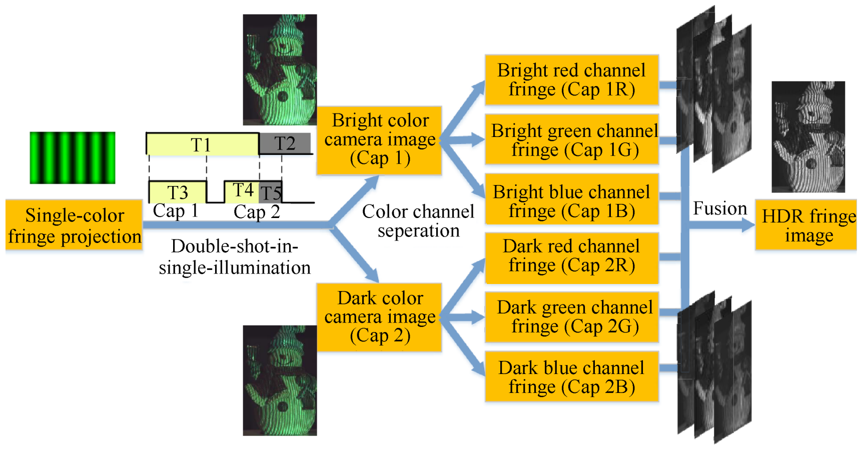

Fig. 6 A schematic diagram of MMF method with RGB camera.[42]

sponse function, and then compress the radiance map based on an attenuation function.

4. Single best measurement

4.1 Adaptive projection intensity

The method of adaptive projection intensity is related to a change on the intensity of the projector in every DMD to avoid issues with low modulation and saturation. Waddington and Kofman[44] figured out a way to use adaptive projection intensity to avoid saturation by analyzing the relationship between projection intensity and camera-captured intensity. It could minimize the root mean square error (RMSE) caused by ambient light and avoid saturation by changing the intensity with pre-calibration. However, the selection of projection intensity is not automated and it can be very time consuming. Aiming to solve this issue, Waddington and Kofman[45] proposed a new technique that could select the appropriate projection intensity to minimize RMSE and avoid saturation. The method can effectively reduce the time of the operation and the error caused by the ambient light. However, it could not get enough dynamic range by only single global projection intensity.

Later on, Waddington and Kofman[34] proposed a method that could change the local projection intensity change to avoid local saturation by two prior projections. It first projects the highest intensity patterns to extract the over-saturation areas, and matches it with the area on the projector through absolute phase obtained by projecting vertical and horizontal fringe images. Then, the low intensity patterns are projected to calculate the adaptive intensity of the areas that correspond to the over-saturation areas in the capture image by the least square method. Finally, the adaptive intensity patterns could be projected to achieve HDR 3D measurement. This process reduced the error caused by the location saturation, but the local intensity change could not satisfy the need of every pixel in the over-saturation area. To solve this issue, Lin et al.[46] changed the projection intensity of each pixel according to the camera's response function. They first projected a uniform pattern with different intensity to calculate the camera response's function. Then, according to the response function, the intensity of every pixel in the projected pattern is calculated with the horizontal matrix generated by unsaturation contour of saturation area. The method considered more effective than multiple projection fusion because it can achieve HDR 3D measurement in pixel levels by single measurement.

Evidently, the effect of adaptive projection intensity method depends on the camera's response function and the calibration of the camera-projector; and both require many different calculations. Li et al.[47] proposed an adaptive projection method that does not depend on any of these features. The method determines the projection intensity of each pixel by a binary search that can calculate the proper intensity only by 8 times for a 255-level projector. As explained in Fig. 7, Chen et al.[48] thought about another method to select the intensity of local saturation area by polynomial fitting with cluster bounding contour. For this method to work, it is only necessary to project a series of pattern at a time, so it can effectively reduce the time of the operation.

Chen et al.[49] also proposed another way to projects a series of orthogonal color fringe patterns with different gray levels in blue and red channel to reduce the time. It first matches with the camera-projector's pixel by absolute phase, and then calculates the proper intensity of every pixel by a series of uniform image projected. The method can get more accurate match between the camera and the projector than the horizontal matrix used for uneven objects.

Yu et al.[50] created a HDR 3D measurement method based on multi-threshold segmentation and mapping relationship between a binocular camera with projector. The method obtained the best projection intensity based on area segmentation and the response function of camera. It matches the oversaturated pixels on the binocular camera images with the projector to reconstruct in 3D according to the pre-calibration parameters.

Liu et al.[51] proposed a method based on adaptive projection for small objects with HDR surfaces. The optimal projection pattern could be calculated only by two uniform patterns and a set of orthogonal fringe patterns based on the camera-imaging model. In the same direction, Xu et al.[52] proposed a new framework for 3D measurement based on the dichromatic reflection model. The key of this framework is to first remove the specular reflection component based on the dichromatic reflection model, then solve the optimal projection intensity according to the fitted energy equation, so it could finally repair the overexposed area.

The method of adaptive projection intensity can change the intensity of every pixel, efficiently reducing the time of the operation. However, it always needs to calculate the camera's response function and consider the pixel matching relationship between camera and projector. For that, a lot of different calculations are necessary, making this method not very suitable for online measurement. However, it can still be used as a supplement for exposure to expand the dynamic range.

4.2 Deep learning

As a new technology, deep learning[53-59] has a lot of potential in the field of image enhancement. Some researchers have already applied it to the field of structured light 3D measurement to get a more accurate phase[60-67]. Yu et al.[63] , for instance, proposed a convolutional neural network (CNN) that was able to extract phase information in both the low signal-to-noise ratio (SNR) and saturation situations after proper training. The CNN was designed to take three-step phase-shifting images as the input, and its results based on the twelve-step phase-shifting calculation are used as ground truth for training. Therefore, the wrapped phase could be calculated by the output of CNN under situations like low SNR or saturation. Liu et al.[60] proposed a new CNN named skip pyramid context aggregation network (SP-CAN), which takes low exposures image as the input feature and considers the HDR image acquired by multiple exposure fusion as the ground truth. As shown in Fig. 8, the SP-CAN utilizes skip connections to extract the outputs of each layer and combines them in a concatenation layer to preserve its advantages of small and large receptive fields. The SP-CAN plays a significant role in image enhancement to get more accurate detailed information about the phase under low SNR situation.

Deep learning is efficient and convenient, and does not have any design manual features. It could perform HDR 3D measurement by single ordinary exposure without any extra equipment after being trained in suitable datasets. For the same reason, its result depends on the training, which requires a considerable amount of data and calculations. Therefore, we should refer to the mature applications of deep learning in other fields, establish professional data sets and accelerate training through transfer learning.

4.4 Other technologies

Ekstrand and Zhang[68] came up with a method to allow the use of an arbitrary exposure time by properly defocusing binary patterns. The method simplifies the exposure adjustments for HDR 3D measurement, but it does not meet the needs of the HDR object by single exposure. Zhong et al.[69] also proposed a new optimal exposure time calibration method to avoid over-saturation in areas of specular reflection. As shown in Fig. 9, they concluded that pixels could behave linearly within an intensity range from 30 to 220. Therefore, the optimal intensity should be close to 220 to get more accurate phase. In theory, the best way to calculate the phase is to make intensity non-saturated. However, sometimes grayscale intensity will over-saturate, causing errors in the process of phase calculation.

Chen et al.[70] analyzed the over-saturation caused by high surface contrast and found that an accurate phase can still be achieved even with over-saturation in some cases. When the fringe period P is an even number, the $N=P/2k$ step algorithm can accurately recover the phase even if the fringe patterns are saturated. When P is an odd number, $N=PK$ step algorithm can also accurately recover phase under the same conditions.

Feng et al.[71] thought about method that could successfully perform HDR 3D measurement by combining fringe and speckle patterns. The idea is to obtain the corresponding phase on another camera image through the speckle pattern to correct the phase error in the saturated area. This method can correct the phase of the saturation area using cameras with different viewing angles. Its effects also depend on the angle.

Hu et al.[72] proposed a microscopic 3D measurement method for shiny surfaces based on multi-frequency phase-shifting. This technique uses the low-frequency phase to replace the phase at the over-saturation area of high-frequency according to the principle that contrast decreases with as the frequency grows under low depth of field.

Liu et al.[60] put forward another optimal exposure selection meth-

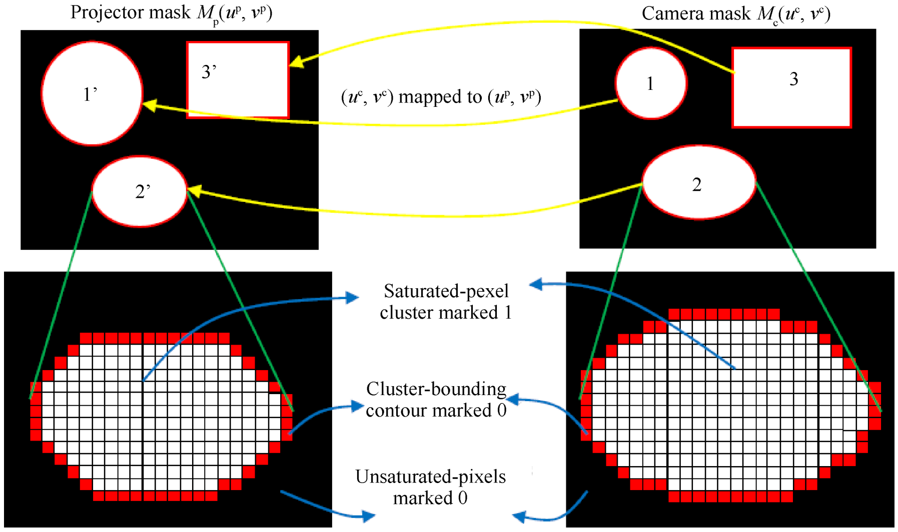

Fig. 7 Procedure used to create projector mask image[48] .

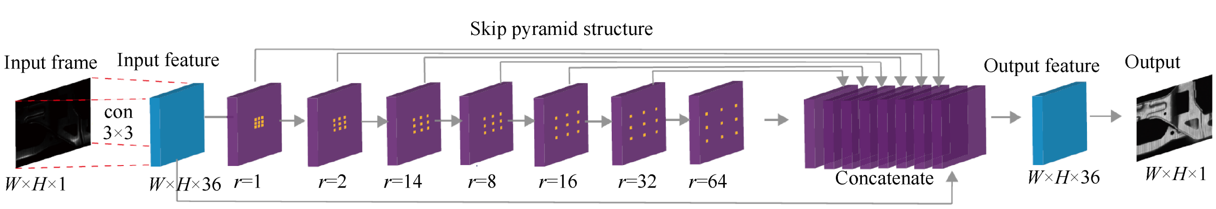

Fig. 8 Skip pyramid context aggregation network (SP-CAN)[60].

od for HDR 3D measurement based on a new quantitative metric that combined modulation and over-exposure.

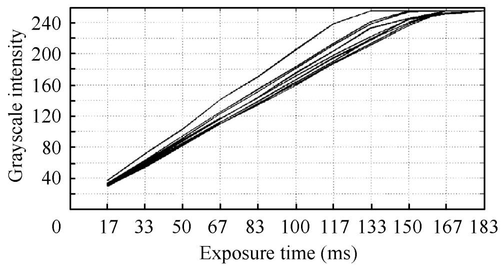

Fig. 9 Behavior of 10 arbitrary peak pixels under different exposure times[69].

5. Conclusion

Despite the advancements of HDR 3D measurement technologies, there are still issues related to the state-of-the-art structured light techniques to solve problems in the field of industrial inspection. In theory, the best solution is to obtain the measurement equipment with a higher dynamic range. Currently, this is remains a challenge, and the feasible methods are still as described in section 2 and 3.

Among all the aforementioned methods, the most widely used one is multiple exposure fusion because of its easy operation and wide applicability. Taking the other techniques into consideration, we believe that there is still room for improvement. The following will briefly analyze the challenges and research directions of each method.

(1) Multiple exposure fusion. his technique is currently the one with the best measurement results and is often used as a comparison standard. Its challenge is how to automatically and efficiently select the appropriate exposure time series, so current studies are on finding a way to automatically select the exposure sequence and increase the measurement speed by reducing the number of exposures or accelerating projection.

(2) Multiple projection fusion. The issues with this method are similar to the ones related to multiple exposure fusion because of its similar principles. Therefore, it is likely to be combined with multiple exposure fusion to achieve higher dynamic range.

(3) Polarization filter. This technique has issues with low modulation of dark areas that can cause large errors. Researchers have been trying to understand how to filter out the specular light with high modulation.

(4) Adaptive projection intensity. This method has great potential because of pixel-level adjustment. However, it can be flawed considering that it is hard to calculate optimal intensity and mapping relationship fast enough. Therefore, many researchers tried to simplify the calculation process of intensity and it remains necessary to conduct more studies regarding this issue.

(5) Deep learning. It is currently the less researched method in the field of HDR 3D measurement, and it has issues with big data set, suitable network structure, and training. For now, we believe the challenge relies on how to select the input and output of this method to get satisfactory results.

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