High dynamic range saturation intelligence avoidance for three-dimensional shape measurement

Bin Zhang, Yuanxin Ouyang, Shuo Zhang
State Key Laboratory of Software Development Environment, School of Computer Science and Engineering, Beihang University, Beijing 100191, P.R.China
Zhangbin_cs@buaa.edu.cn,oyyx@buaa.edu.cn,zhangshuo1990@cse.buaa.edu.cn

***Abstract*—There always exists an intractable challenge in three-dimensional (3D) object surface measurement that it is difficult to deal with the scene with a large range reflectivity or specular reflection. This paper presents a novel 3D measurement technique: high dynamic range saturation intelligence avoidance (HDRSIA), which is based on the multi-exposure principle. This method divides the object surface into several parts according to the color distribution and leverages the modified curve fitting technique to capture the best exposure time for each part, intelligently and precisely. A set of modified fringe images are then composite to a complete image contained the information of brightness part and darkness part. Experiment results verify that the proposed method can build the accurate 3D point cloud model for object surface with high dynamic range of surface reflectivity variation.**

***Keywords*-3D measurement, high dynamic range, intelligence, modified curve fitting, image fusion**

I. Introduction

The three dimensional (3D) shape measurement technique is more and more popular and has been applied to many fields, such as industrial manufacturing, reverse engineering, biological sciences, and clinical medicine. The 3D measurement offers advantages of high-speed, high-efficiency and high precision, thus there is an increasing demand for market. Currently, the binocular structured light measuring technique is mainly used in the 3D measurement for surface reconstruction, and it applies the phase-shifting fringe-projection method to measure the object surface. A set of phase-shifted fringe images are projected by the projector onto the object to be measured, and the deformed patterns on the object surface are captured by the left and right cameras beside the projector and then be used to obtain the phase map. After being left-to-right matching, the phase of object converts to the point cloud information to build the 3D model.

For general measurement system, there often encounters the following two questions:

- First, because of the high object illuminance or high surface reflectivity, when the input light intensity is greater than the maximum capturing capacity of the CCD sensor, it will cause the saturation of captured pixels.
- Second, there is a high contrast in the scene, which has a large range of color distribution from 0 to 255(in the 8-bit camera). If the system setting is adapt to the surface with high reflectivity, regions information with low reflectivity will be lost. If areas with low reflectivity are well captured, then those with high reflectivity cannot be obtained due to the sensor saturation.

The commonly existed problems described above have a negative influence on the measurement accuracy. In order to solve the above problems, the methods conducted by researchers focus on the following aspects:

To change the object surface itself. Photographic developer is sprayed on the object surface to make the color distribution more uniform, thus the specular reflection would be changed to the diffuse reflection. These methods are simple and fast, and it is convenient for the measurement with no specific need of the object surface. However, they cannot be widely applied to 3D measurement system as it changes the surface information of object, which is not suitable for clothing, machine components and so on. In addition, this kind of method cannot meet the requirement of a high-precision surface reconstruction and is only applicable to the rough surface restoration. To start from the hardware system. Add physical filters, such as optical filter or diffuser, in front of the camera and projector to alter the propagation direction of the light beam so that the strong reflection would be diverged to several angles. Besides, on the one hand, multiple camera viewpoints ensures that via camera-viewing angle combination, measurement can avoid saturation in previously saturated image regions; on the other hand, multiple projection directions guarantees that at least one projector-lighting would not cause saturation. But the system is too complex to obtain the effective 3D data.

To adjust exposure. There are several ways to change the exposure time in 3D measurement system, such as adjusting the aperture of camera lens or the aperture of the projector lens, adjusting the camera exposure time by change the parameters on the software system and so on. As adjusting system exposure time has advantages of simple step and shortening operating time, and it has minimal impact to the measurement accuracy, currently, this kind of approach is widely used in 3D shape measurement with a large range of reflectivity. Exposure time can be adjusted from the camera interface via software, and thus it is independent from the hardware, and it is effective to increase the signal-to-noise ratio (SNR) of images, thereby the accuracy of the data acquisition is increased.

This paper proposes a new method High dynamic range saturation intelligence avoidance(HDRSIA) based on the principle of the multi-exposure. Aiming at the high-contrast scene, this method can be used in most structure light system with an advantage of less human intervention. Our experiment results prove that when dealing with high dynamic range(HDR) of surface reflectivity, proposed method has much improvement for traditional three-dimensional object measuring system to obtain high-precision surface data and reduce the cost of the hardware system in the maximum degree.

This paper is organized as follow, section 2 introduces some kinds of methods solving the HDR problem; section 3 describes related techniques used in the measurement system; section 4 details the experiments to validate the algorithm; and section 5 summarizes this article.

II. Related Work

A. Hardware System

Conventional approaches are mainly starting from the aspect of hardware settings and have several types to solve the problems of high dynamic range and high reflectivity. Qing et al. [1] added appropriate color filters in the front of the camera and projector to separate the input light so that a certain color light can be pass through. Mohit Gupta et al. [2] put a diffuser between the light source and the scene. Each pixel would be illuminated by an extended source in the scene because every illumination plane cross the linear diffuser along the diffusion axis. The two methods above are considered from the way of the system structure by means of placing physical filters in front of the camera and projector. The purpose is to weaken the intensity of the incident light thereby eliminating the high reflection of object surface. However, these methods not only reduce the light intensity of regions with high reflectivity but also the intensity in non-saturated regions, which brings about a reduction in measurement accuracy as the SNR declines. Besides, Gui-hua Liu et al. [3] proposed a method combining both binocular and monocular structured light technique. It performs object shape measurement via multiple angles to reduce the errors caused by specular highlights reflection and diffused darkness. In addition, there is another measurement approach [4] similar to multiple angles, which captures fringe images via a multi-projection direction. The two methods both adjust the system settings to ensure that there is no saturation phenomenon existed in the captured fringe images at least at one direction. Nevertheless, they are time-consuming and may increase the complexity of the hardware system, which lead to the difficulty of data acquisition and calculation process.

B. Fringe Pattern

Another kind of methods of avoiding image saturation is projecting the modified fringe patterns on the object surface. Waddington and Kofman developed a new method by adjusting the maximum intensity gray level of fringe pattern [5–7]. Various sets of phase-shifted sinusoidal fringe patterns were adjusted to different maximum gray level, which gradually decreased from 255 to the lower value with a constant step S. Deformed fringe patterns, which were reflected by the object surface, were captured by the camera. Then choosing the highest intensity without saturation from a set of phase-shifted images were used to construct composite images pixel-by-pixel. This method can solve the problems of the image saturation when measuring the shiny objects especially with the influence of ambient light. Nevertheless, reducing the peak gray level of the fringe pattern would reduce the contrast of the captured image and thus lead to the lower SNR which caused the decrement of precision. Besides, for the HDR scene, this method does not guarantee the validity of the data in the dark regions. In addition, Babaie et al. [8] proposed a new approach to capture the dynamic range of object surface in 3D measurement, they altered the intensity of the projection pattern recursively based on the feedback from the images captured by the camera. However, this method has a complex iterative process and compresses the color distribution of the measured scene, thus it has a negative effect on the SNR.

C. Exposure

At present, changing the exposure time is the main-stream approach and many researchers have developed several kinds of new methods based on the exposure time. Generally, adjusting the system exposure time is divided into two categories, one is considered from the hardware system, such as adjusting the aperture of the camera lens or the aperture of the projector lens, in order to alter the exposure time; the other one is considered from the software aspect which changes the exposure time by set the parameters on the software system, such as to adjust the camera exposure time, the camera gain, and the projector gain. Among these approaches, adjusting the aperture of the hardware system would change the relative position between the projector and camera, thus leading to the measurement errors because of the decline of the calibration precision. To measure the object surface with a large range of reflectivity, Zhang et al. [9] presented a new method of high dynamic range scanning technique that different exposure time was set to fit the complex scene. For the regions with low reflectivity, there would be an extension for longer exposure time. While for the regions with a high reflectivity, exposure time would be reduced. Then a set of phase-shifted fringe images were captured to synthesize the good quality images by choosing the valid pixels in each image. Although, this method provides a solution for high contrast surface measurement, it is subjective determined by personal experience which lacks the quantitative calculation of specific exposure time. Jiang et al [10, 11] proposed a new method High dynamic range fringe acquisition (HDRFA) to eliminate the impact of high light. It first simultaneously changed the camera exposure time and the fringe pattern gray level to capture a group of raw images. Then the final composite image was constructed to choose the pixels with largest intensity modulation from different exposure images. With the largest modulation of the pixels in the images, the SNR and the data accuracy would be increased. However, it is complicated to initialize the parameters of the algorithm. Moreover, to determine the value of the parameter according to the specific color distribution of object surface is difficult. For the more, an auto exposure technique and an automated high-dynamic-range 3D optical metrology was bring up in [12], which could predict the required exposure time adaptively. They both use the binary defocusing technology and thus could adjust the exposure time casually without the restraint of the projector's refresh frequency. But the algorithm increases the difficulty of system calibration, and thus cannot be applied to fixed focus projector measurement system. Based on HDR principle, an adaptive multi-exposure technique, was proposed by [13]. With the combination of the two orthogonal polarizers, a histogram statistics is performed to obtain the grayscale distribution of the scene, then corresponding optimum exposure time for each pixels can be acquired. While this method increases the manual operation, it is not intelligent when choosing the predicted exposure time. What is worse, altering the angle via human intervention reduces the calibration precision.

In summary, the above methods cannot intelligently give the accurate exposure time when dealing with high contrast scene or measuring the surface with high reflection. The method HDRSIA proposed in this paper uses the conventional binocular measurement system combined with the four-step phase-shifting algorithm in order to solve the problem. Captured fringe Images is mapped to grayscale histogram space from pixel space, and the least squares curve fitting algorithm is used to find multiple peaks and valley. Thus intelligent selection an optimal exposure time for each cluster.

III. PRINCIPLE

A. *four-step phase-shifting algorithm*

Phase-shifting method is widely used in the 3-D object surface measurement, due to its fast measurement speed less sensitivity to surface reflectivity variation and high accuracy [14]. The basic principle of phase shifting is: captured multiple fringe images, which have a certain phase shift, are used to calculate the initial values of the deformed surface which containing three-dimensional information [15]. Currently, there are a variety of phase-shifting algorithms, and each algorithm stability and error response are not the same, therefore, the selection of the phase-shifting algorithm has an important influence on subsequent phase calculation and reconstruction precision [16]. In our system, we use a four-step phase-shifting algorithm to obtain the phase grating. The fringe pattern images I_i for 4 step phase-shifting patterns are as follows:

$$I_i(x, y) = A(x, y) + B(x, y)cos[\phi(x, y) + P_i], \tag{1}$$

Where $A(x, y)$ is the average intensity, $B(x, y)$ is modulation intensity, P_i is the phase-shifting step of the each fringe image i, and in our measurement, the phase steps of four images are set as 0, $\pi/2$, π, $3/2\pi$. $\phi(x, y)$ is the main phase value which is to be calculated. Where $A(x, y)$, $B(x, y)$ and $\phi(x, y)$ are three unknown parameters, thus, we use four phase-shifted images respectively to compute these values. The equations are as follows:

$$\begin{aligned}
I_0(x, y) &= A(x, y) + B(x, y)cos[\phi(x, y) + 0 * \pi/2],\\
I_1(x, y) &= A(x, y) + B(x, y)cos[\phi(x, y) + 1 * \pi/2],\\
I_2(x, y) &= A(x, y) + B(x, y)cos[\phi(x, y) + 2 * \pi/2],\\
I_3(x, y) &= A(x, y) + B(x, y)cos[\phi(x, y) + 3 * \pi/2],
\end{aligned} \tag{2}$$

According to Eq. (2), then the $\phi(x, y)$ can be calculated:

$$\phi(x, y) = \arctan\left(\frac{I_3 - I_1}{I_0 - I_2}\right), \tag{3}$$

The main phase value $\phi(x, y)$ is unique in a single phase period, but there are multiple grating strips in the whole measurement space, and the shape of $\phi(x, y)$ has a zigzag profile. Hence, it is necessary to unwrap the main phase value by 2π to obtain the continuous absolute phase value $\Phi(x, y)$, and then the absolute value is used to calculate the phase difference between the left and right cameras, combined with the original system calibration parameters, the three-dimensional point cloud model can be built [17].

B. *fringe pattern images analysis*

Traditional binocular structure light system consists of a digital projector, two industrial cameras and a computer for calculation. Usually, to form a fringe image includes three steps: fringe projection, object reflection and image capture. The phase-shifted fringe images are projected onto the object and are reflected by the object surface. Camera captures the deformed fringe patterns and sends them to the computer for the subsequent calculations. In the actual experiment, the light entering the camera usually consists of three parts: the first part comes from the light beams which are projected by the projector and are reflected by the object surface, namely the signal part; the second part comes from the ambient light reflected by the surface and passed into the camera; the last part is the ambient light direct into the camera. The influence of different sources of luminance in capturing fringe pattern images by the camera is shown in Fig. 1. For simplicity, we

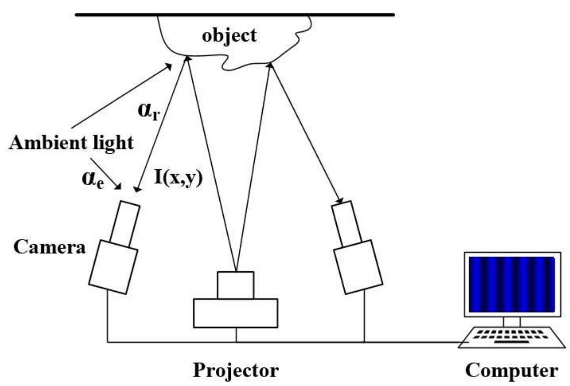


Figure 1. Binocular Structure Light System

rewrite the Eq. (1) as:

$$F(x,y) = I_i(x,y) = A + Bcos\theta \tag{4}$$

Thus, the fringe intensity map is given by the following equation:

$$I = Kr(x,y)[F(x,y) + a_r(x,y)] + Ka_e(x,y) \tag{5}$$

where K is the camera parameter and $r(x,y)$ represents the reflection of the object surface. $a_r(x,y)$ and $a_e(x,y)$ are the noise caused by the ambient light.

Combined the Eq. (1) with Eq. (5), the intensity modulation can be expressed as

$$I''(x,y) = Kr(x,y)B, \tag{6}$$

and the average modulation is

$$I'(x,y) = Kr(x,y)[A + a_r] + Ka_e, \tag{7}$$

the variation of I'' and I' makes the captured fringe pattern having the full range of projected intensities. The sum of I'' and I' is the max intensity while the difference is the min intensity. What‘s more, the data modulation is

$$\Omega(x,y) = \frac{I''(x,y)}{I'(x,y)} = \frac{r(x,y)B}{r(x,y)[A + a_r] + a_e} \tag{8}$$

which determines the quality of image.

From Eq. (6), for different object surface with a large range reflection $r(x,y)$, in order to get an appropriate intensity modulation, we only can adjust the camera parameters K. if the $r(x,y)$ is small, namely the region is dark, K has to be high; on the contrary, K has to be low. And we can change the camera parameter K by adjusting the exposure time, and the relationship between K and t is:

$$K = P_c t \tag{9}$$

where P_c is a constant parameter, so K can be replace by t.Besides, data modulation $\Omega(x,y)$ is critical to the image data, the closer to 1, the higher quality. From Eq. (8), we can see that it is necessary to eliminate the influence of the ambient light, thus, it can achieve the more precious measurement.

C. HDRSIA principle

HDRSIA, namely High Dynamic Range Saturation Intelligent Avoidance, is developed on the basis of multi-exposure. Zhang et al proposed the idea of multi-exposure and conducted experiment based on the personal experience that measuring the surface with low reflectivity used a large exposure time and the surface with high reflectivity used a small exposure time. It is a pity that the parameters are not quantitative. HDRFA quantized the parameters of exposure time and fringe gray level. This method was designed to obtain the highest fringe modulation intensity of pixels in order to forming high-quality fringe images. However, it is difficult to give the reasonable values of parameters, hence it needs to verify the reliability of selected values in multiple experiments. Yu et al presented a new method based on the assumption that a single exposure time can provide enough exposure for surface with a small variation range of reflectivity. This method divided the scene into several clusters according to the gray level distribution and thus chose the best exposure time for each clusters. Nevertheless, the process of choosing is manual instead of algorithm. Therefore, the purpose of HDRSIA is able to calculate the optimal exposure time with less human intervention in order to get a high SNR fringe images.The idea of HDRSIA, which absorbs the essence of the above algorithms, is developed to solve the problem of the object surface with a large range of reflectivity.

From the section B fringe pattern images analysis we know that: when ignoring the impact of ambient light, image intensity can be expressed as

$$I = P_c t r I^P \tag{10}$$

where t is the camera exposure time, and P_c is the camera parameter that usually will be constant. r is the surface reflectivity and I^P is the projected intensity which plays the signal part of the image intensity. Thus, from the Eq. (10) we can deduce when the projected fringe intensity remains unchanged, exposure time can determine the quality of pixel intensity, and the equation can be deformed as

$$I = Ct \tag{11}$$

In Eq. (11), C maintains relatively constant and the equation shows that exposure time and the final image intensity have a similar linear relationship. Thus we can adjust pixel intensity via setting optimal exposure time to obtain the optimal pixel which has the largest intensity gray level but without saturation.

$$I_{opt} = Ct_{opt} \tag{12}$$

Then we preset parameters exposure time t_{pre} and capture the corresponding intensity I_{pre} to calculate the optimal intensity. The relation of I_{pre} and t_{pre} is:

$$I_{pre} = Ct_{pre} \tag{13}$$

Then, combined with Eq.(12) and Eq.(13), we can deduce the optimal exposure time.

$$t_{opt} = \frac{I_{opt}}{I_{pre}} t_{pre} \tag{14}$$

In the equation, the optimal intensity is usually set as 254. However, it is impossible to calculate every pixel‘s best exposure time, thus it is necessary to select a single exposure time which represents surface with a small range variation of reflectivity.

Generally, different surface reflectivity shows different optical properties that for large reflectivity regions, they are brighter while for low reflectivity regions, they are darker. Thus, these features showed in the captured image are that the gray level in high reflectivity areas are usually greater than 200(for a common 8 bit camera, and the CCD‘s capability is 256 gray levels), some parts are more close to 255, or even equal to 255. In contrast, areas of low reflectivity often below 50 and part of regions are close to 0. For an image with large resolution, there is only 256 gray levels which leads to a number of points on the same gray level. We assume that

- For the pixels with the same gray levels, their surface has the same reflectivity or they are located in the different position of surface with the same material;
- For a point and the regions in the vicinity of the point, they usually present little difference of the gray level.

According to these features above, the entire image can be divided into several zones Z_i based on the pixel gray level. In the same zone, there is a small range of the pixels‘value. For each zone, we find out a gray level which has the maximum number pixels in this gray level, and we define it as the feature label of the zone, denoted by $Gray(i)$. The feature label is used to represent the zone‘s optimal exposure time.

D. Modified Curve Fitting

To find the $Gray(i)$ of each zone Z_i intelligently, we calculate the histogram of the scene and use curve fitting algorithm to automatically select the best value. When obtaining the histogram of the scene to be measured, the gray level distribution of the image does not always uniform and smooth, and there would appear multiple peaks and valleys in the histogram, thus it is difficult to decide the best value. General method performs curve fitting method via least square to divide the whole image into several zones and manually choose the significant peak and valley of the zone. The traditional least square method has a good effect on linear data fitting and monotonous curve fitting, also it can meet the requirement of single-peak data fitting. However, for the multi-peak curve fitting, this method cannot perform once to obtain a good result, sometimes it will cause serious mistakes, therefore, it is necessary to modify the least square method to meet the requirement for the image with multiple peaks and valleys.

Under the condition of above problem, we modify the conventional least square method and combine the method in [18] to solve the problem. We take three steps to modify the least square method: filtration, segmentation, and fitting. The specific procedures are as follow:

- Filtration. Because the color distribution of measured scene cannot be known in advance, it is difficult to divide the image data into a certain number of groups, thus, we first need to calculate the average intensity value of the whole image. If the number of peaks is low and the width of peak is narrow, then for all the data, the amount of data belonging to the peak region is relative small, and the calculated average intensity is close to the background intensity. If we simply choose the average intensity as the standard for truncating data, under the condition of dark background, it is prone to filter noise data when there exists a mount of noise data, which causes a negative influence on measurement precision. Therefore, it is necessary to add a value on the average intensity. The value is neither too large which leads to incomplete data acquisition nor too small which caused the noise disturbance. It is appropriate to set the value as about 5% of the maximum intensity among all data. Besides, we define the sum of the two values as the valid standard in Eq (15)
$$V = avg(I) + 5\% I_{max} \tag{15}$$
where V represents the valid standard. After the valid standard is determined, we compare all data with the valid standard, if the data value is greater than valid standard, the data is considered valid, otherwise discard.
- Segmentation. The standard of data segmentation is to first sort the valid data according to the intensity of data, which based on the dynamic principle. After sorting, the step between adjacent data is not necessarily set as 1, because there is some bad points removed in step 1, or the data of two peaks has a big gap, which is used to distinguish different groups of data. The big gap must be set over than a certain value C, thus if the distance of two adjacent points is greater than C, then the following data is divided into the next group, otherwise, it belongs

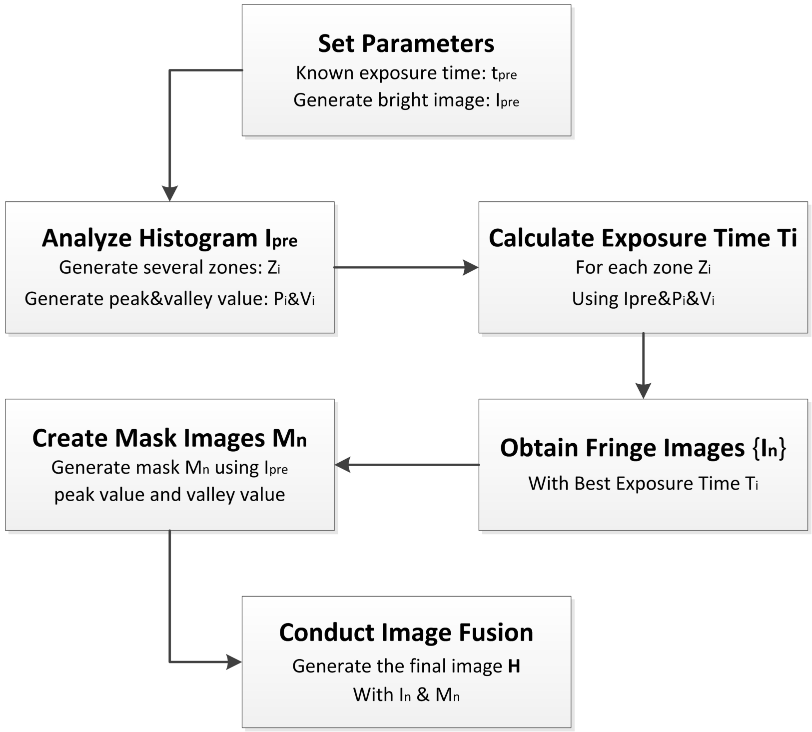


Figure 2. HDRSIA flow chart

to the last group. If the current point is the last one, it needs to be compared with the previous point. And if the distance of two points if larger than C, it is obvious that the current point is the bad point which can be take out; on the contrary, it is divided into the last group. Through the steps above, the valid data can be divide accurately into several groups.

- Fitting. After the filtration and segmentation, the data is correctly divided into several groups and the noise data from background is removed mostly, then we perform the curve fitting technique to make the curve smoother and easier to select peaks. Generally, the least square method is applied to do curve fitting.

E. Procedures

Fig. 2 shows the processing flow chart of the proposed algorithm. As described in Fig. 2, there are six steps to do the image fusion.

1. Initial the parameters of the algorithm. We predetermine the exposure time t_{pre} of camera in a relatively low level in order to obtain the uniform bright image I_{pre} without pixel saturation. Besides, to capture a high SNR fringe image, it is need to eliminate the influence of ambient light, thus, we can conduct experiment in an enclosure space without light or use a black background.
2. Take gray-level histogram of I_{pre}. We Analyze the histogram of I_{pre} to form several zones Z_i and do the curve fitting to intelligently generate the peak value P_i and the valley value V_i of each zone.
3. Calculate exposure time T_i. According to the equation (14), using P_i and V_i to calculate the optimal exposure time for each zone Z_i.
4. Obtain fringe images. Based on the principle of HDR, capture a set of fringe images at four different phases using the optimal exposure time of each zone. Then, these fringe images are used to form the final image with high quality.
5. Create mask images. It is need to create mask images to select the optimal pixels from each set of images. According to the V_i of each zone, mask images are described as follow:

$$M_i(x,y) = \begin{cases} 1 & \text{if } V_{i-1} < I_{pre} < V_i \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

6. Conduct image fusion. Mask images are used to extract effective part of each image and then these parts are synthesized to a complete image $H(x,y)$ which has a better recovery for both bright surface and dark surface, and the equation is described as follow:

$$H(x,y) = \sum_{i=1}^{N} M_i(x,y) * I_{opt}^{i}(x,y) \tag{17}$$

where N represents the total number of zones, I_{opt} is the fringe image with the exposure time T_{opt}. The process of image fusion can be performed in two steps: first, using mask image extract intensity values from each fringe image and then add all extracted parts to a new fused image. What's more, the experiments below verify proposed algorithm.

IV. Experiments

A. System Setup

For the experiments, we use a binocular structured light system to conduct the 3D shape measurement. As shown in Fig. 3, the measurement system is made up of a DLP (Digital-light-processing) projector and two industrial cameras. The DLP projector used in experiments is TI lightCrafter PRO 4500 with a resolution of 1280*800. This kind of product use the light source of single-blue LED which offer the advantage of high resolution and high precision, besides, the refresh frequency of projector is 120 Hz. The camera employed in the research is Catch-Best MU3C500M with a resolution of 2549*1920. Four-step phase shifting algorithm is applied to the measurement. We use fringe images with three different frequencies of 59, 64 and 70. In addition, the gray level of fringe image range from 40 to 220, which is beneficial to enhance the accuracy of image pixels. We conduct experiments with two different scenes to test the quality of our algorithm. The first scenario consists of a plaster model of Marx, a set of building blocks and a Samsung Tab Book Cover, and the second one includes a metal bracket and the Samsung Tab Book Cover. We both use conventional method and proposed method to construct the 3D information of models, and then make comparisons of these two kinds of solutions. It is noteworthy that there is a small difference of the captured images between the left and right camera, thus we all use left camera images to illustrate the following experiments.

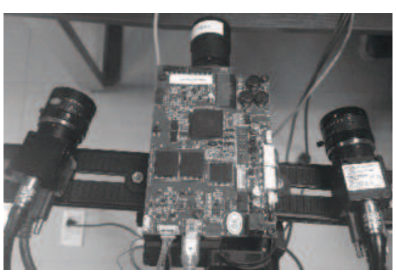


Figure 3. System Setup

B. HDR Measurement for High-Contrast Scene

In the first experiment, a plaster model of Marx, a set of building blocks and a book cover are put in the scene to be measure. It is obvious that the surface of the plaster model is brighter because of a higher reflectivity, and the building blocks are moderate while the surface of book cover is much

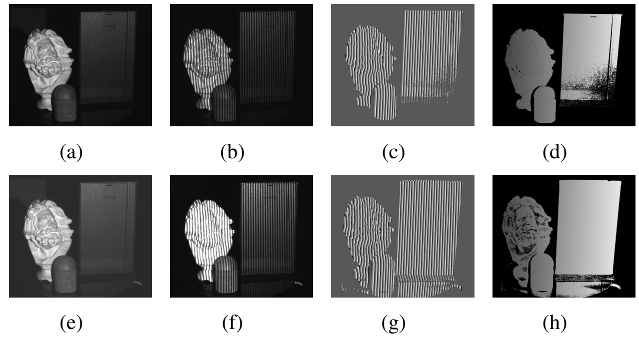


Figure 4. experiment results with a low level exposure time and a high level exposure. 4(a)dim object scene. 4(b) captured fringe image in low level. 4(c) relative phase map in low level. 4(d) unwrapped phase map in low level. 4(e) bright object scene. 4(f) captured fringe image in high level. 4(g) relative phase map in high level. 4(h) unwrapped phase map in high level.

lower relatively, therefore, there is a large reflectivity in the scene which can lead to losing information.

First of all, we use the conventional method with a single exposure time to capture the scenario. In order to acquire the accurate surface data of the plaster model, we set the exposure time at a relative low level. Fig. 4 illustrates the process of measurement with the conventional method. Fig. 4(a) is the captured image with a uniform light in low level, Fig. 4(b) is the obtained fringe image and from the image we can see that the whole image is dim and some portions of the book cover already cannot be seen clearly. Then, the fringe image is used to calculate the relative phase map, shown in Fig. 4(c). And Fig. 4(d) shows the absolute phase map after phase unwrapping, As shown in the picture, although the majority part of the plaster model was recovered with a single lower exposure time, some hole occurred in the bottom portion of the book cover, which leads to the measurement errors. Second, the exposure time is set to a high level to ensure the definition of the dark regions. Fig. 4(e) is the measured scene with a higher exposure time and the brightness is larger than before. And the fringe-shifted image is captured in Fig. 4(f). Fig. 4(g) is the relative phase map after phase calculation and the final result of absolute phase map is shown in Fig. 4(h). With a higher exposure time, the intensities in the book cover regions have a reasonable level that most pixels can be obtained by the camera, while some areas in the plaster model regions reach to the peak intensity of the CCD sensor which causes the image saturation.

Then, we use the proposed method HDRSIA to do the measurement. First, we need to initialize the system parameters by adjusting the exposure time to an appropriate level, so that there is no pixel saturation appeared in the scene. And then we obtain the preset exposure time T_{pre}, which $T_{pre} = 60.53ms$, and capture the color distribution map I_{pre}, which is shown in Fig. 5. Then, the histogram of I_{pre}

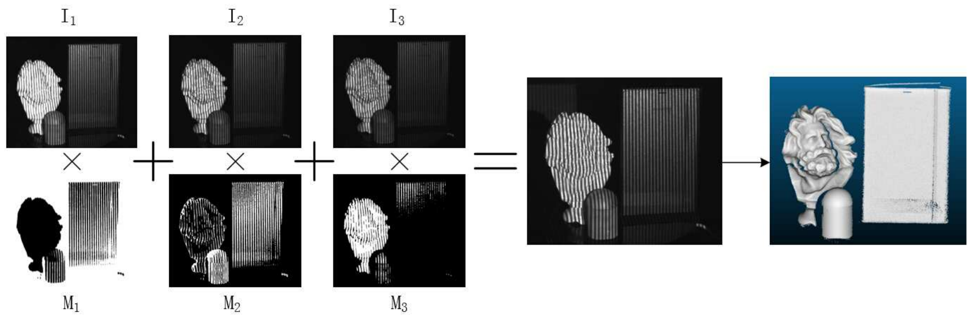
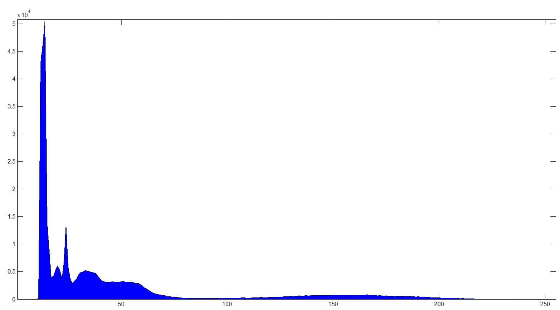
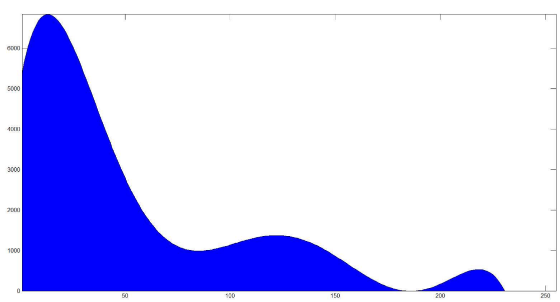


Figure 6. Image Fusion.

is calculated, and we use the curve fitting method proposed above to smooth the histogram curve. The results of before and after using the curve fitting method are shown in Fig. 5, and from the results we can see that the two curves have a big difference. Via the curve fitting method, the whole image



(a)



(b)

Figure 5. Histogram of I_{pre}. 5(a) origin color distribution. 5(b) color distribution after curve fitting.

is divided into three distinct zones, and the peak value and the valley value of each zone can be intelligent obtained, therefore, it is easy to calculate the optimal exposure time of each zone. These specific values of parameters are shown in Table I. Subsequently, for each best exposure time, we capture the fringe images I_{opt}^{i}(i=1,2,3) respectively. Then the mask of each image is calculated based on the range of each zone, which is used to extracting the most effective part of each image to form the final composite image. The process of image fusion is shown in Fig. 6. For the four-step phase-shifted images, they all take the same procedures to do the image composition, and these synthetic images then are used for subsequent calculations. The final 3d point cloud result is shown in the right of Fig. 6.

Compared with the single-exposure experiment, the HDRSIA approach has a large promotion for the high-contrast scene. By using the HDRSIA approach, the object surface can be intelligently divided into several parts, and it is easy to obtain corresponding optimal exposure time, respectively. Then the most effective part of each zone can be extracted under the condition of best exposure time, and the object surface can be recovered completely. The experiments prove that the HDRSIA algorithm has a good effect when solving the HDR problem, and it improve the accuracy of the data.

C. Specular Reflection Measurement for Metal

To further verify the reliability of the proposed algorithm, we performed another set of experiments. The second set of experiments include a metal bracket placed in the left bottom and a book cover located in the right, respectively. The surface of the metal bracket is much more smooth and it will generate the specular reflection. Similarly, we both use traditional method and proposed method to conduct the experiments. In the traditional method, we set the exposure time in two levels: low level and high level, and then capture the fringe images with the preset exposure time. The results of the conventional method are shown in Fig. 7. From the figure we can see that whether the exposure time is in the high level or the low level, some information are lose, and we cannot obtain a complete recovery of the object surface.

Then, the proposed method was applied to the scene. A

Table I

	$Zone_1$		$Zone_2$		$Zone_3$	
Peak Value	29		123		217	
Valley value	9	78	78	173	173	238
Exposure Time	$525.71ms$		$123.90ms$		$70.23ms$	

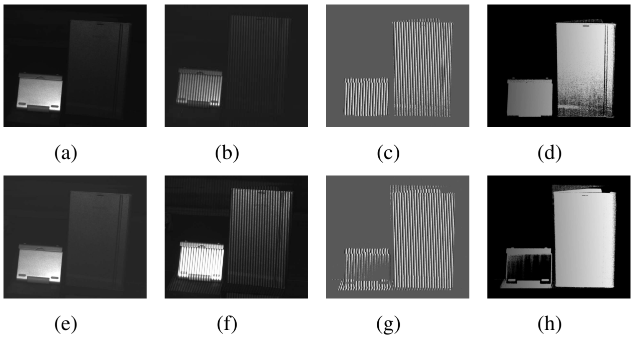


Figure 7. Experiment results of Metal model. 7(a)dim object scene. 7(b) captured fringe image in low level. 7(c) relative phase map in low level. 7(d) unwrapped phase map in low level. 7(e) bright object scene. 7(f) captured fringe image in high level. 7(g) relative phase map in high level. 7(h) unwrapped phase map in high level.

uniform image was first projected onto the object to obtain the gray distribution diagram I_{pre} corresponding with the preset exposure time T_{pre}. The T_{pre} was set as $45.40ms$ Then, the I_{pre} was used to calculate the graylevel histogram, and after being curve fitting, several zones were separated and we could easily obtain the peak value and the valley value of each zone, and thus the best exposure time for each zone could be calculated. In the experiment of metal, the whole scene was divided into two zones, and the parameters of each zone are shown in the Table II. And the histogram of object is in Fig. 8. Like the experiment one above, we

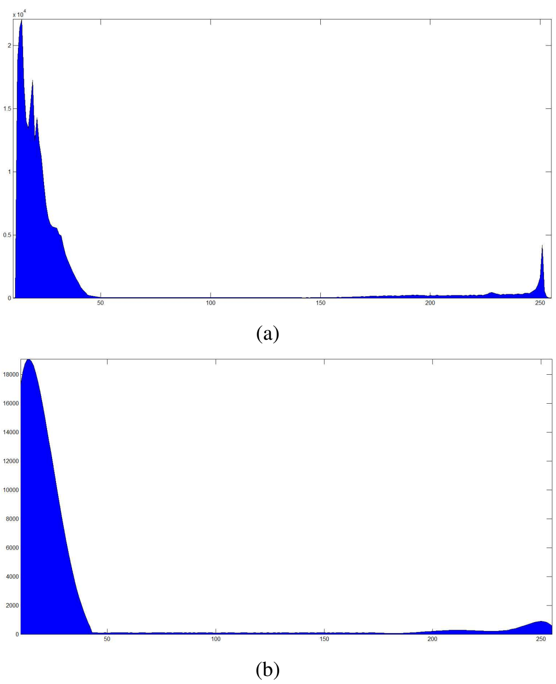


Figure 8. Histogram of I_{pre}. 8(a) origin color distribution. 8(b) color distribution after curve fitting.

did image fusion of each captured image to select the best pixels intensity. Finally, all composite images were used to build the 3D point cloud model of the object. Fig. 9 gives the all middle results and final results of the measurement.

From the figures we can see that the surface of a metal bracket has been recovered mostly, while the part of book cover also has a good effect. Although there is a little flaw on the metal surface, the proposed method has a significant improvement for the 3d surface recovery.

Table II

	$Zone_1$		$Zone_2$	
Peak Value	17		238	
Valley value	10	75	75	255
Exposure Time	$678.32ms$		$48.45ms$	

V. Conclusion

We proposed a novel solution, aiming at HDR scene, by introducing the HDRSIA to 3D object measurement. This new method allows a binocular structured light system to measure the objects surface with a large range reflectivity and can generate an accurate point cloud model. The H-DRSIA method obtains the color distribution of the object surface and divides the whole scene into several zones. Then combined with the curve fitting approach, the optimal exposure time for each part can be calculated. Eventually, a set of modified fringe images are compounded to a complete image which contains the surface information of the brightness part and darkness part simultaneously. The proposed approach offers the advantage that it can determine the best exposure time for each part intelligently instead of manually, which is benefit to choose the highest intensity pixel but without saturation, and thus the SNR of image has a large improvement. In addition, there are no special requirements for the hardware system, so the method can be applied to the general three-dimensional measurement system. Furthermore, the parameters of system are purely altered by the software via the HDRSIA algorithm and there is no additional hardware cost which ensures the accuracy of the system calibration. However, it is noteworthy that no extra physical filters are added to the system, therefore, there are still some defects. For example, when dealing with the specular reflection, some information will be lose because of the strong projected light. Thus, further research will continuously focus on the specular reflection to optimize the proposed method.

Acknowledgment

This work was partially supported by the Natural Science Foundation of China (NSFC) under grant 61472019, the National High Technology Research and Development Program of China (No.2013AA01A603), and the Aeronautical Science Foundation of China (No.2013ZC51), and the National Science & Technology Pillar Program under grant 2015BAF14B00.

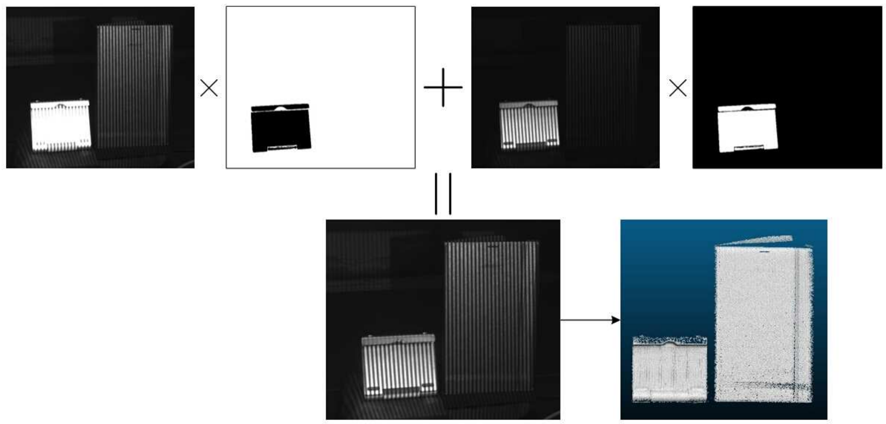


Figure 9. Measurement results of Metal.

References

[1] Q. Hu, K. G. Harding, X. Du, and D. Hamilton, "Shiny parts measurement using color separation," in *Proc. SPIE*, vol. 6000, 2005, p. 60000D.

[2] S. K. Nayar and M. Gupta, "Diffuse structured light," in *Computational Photography (ICCP), 2012 IEEE International Conference on*. IEEE, 2012, pp. 1–11.

[3] G.-h. Liu, X.-Y. Liu, and Q.-Y. Feng, "3D shape measurement of objects with high dynamic range of surface reflectivity," *Applied optics*, vol. 50, no. 23, pp. 4557–4565, 2011.

[4] R. Kowarschik, P. Ku, W. Schreiber, G. Notni *et al.*, "Adaptive optical three-dimensional measurement with structured light," *Optical engineering*, vol. 39, no. 1, pp. 150–158, 2000.

[5] C. Waddington and J. Kofman, "Sinusoidal fringe-pattern projection for 3-D surface measurement with variable illuminance," in *Optomechatronic Technologies (ISOT), 2010 International Symposium on*. IEEE, 2010, pp. 1–5.

[6] D. Li and J. Kofman, "Adaptive fringe-pattern projection for image saturation avoidance in 3D surface-shape measurement," *Optics express*, vol. 22, no. 8, pp. 9887–9901, 2014.

[7] C. Waddington and J. Kofman, "Camera-independent saturation avoidance in measuring high-reflectivity-variation surfaces using pixel-wise composed images from projected patterns of different maximum gray level," *Optics Communications*, vol. 333, pp. 32–37, 2014.

[8] G. Babaie, M. Abolbashari, and F. Farahi, "Dynamics range enhancement in digital fringe projection technique," *Precision Engineering*, vol. 39, pp. 243–251, 2015.

[9] S. Zhang and S.-T. Yau, "High dynamic range scanning technique," *Optical Engineering*, vol. 48, no. 3, pp. 033 604–033 604, 2009.

[10] H. Jiang, H. Zhao, and X. Li, "High dynamic range fringe acquisition: A novel 3-D scanning technique for high-reflective surfaces," *Optics and Lasers in Engineering*, vol. 50, no. 10, pp. 1484–1493, 2012.

[11] H. Zhao, X. Liang, X. Diao, and H. Jiang, "Rapid in-situ 3D measurement of shiny object based on fast and high dynamic range digital fringe projector," *Optics and Lasers in Engineering*, vol. 54, pp. 170–174, 2014.

[12] L. Ekstrand and S. Zhang, "Automated high-dynamic-range three-dimensional optical metrology technique," in *ASME 2014 International Manufacturing Science and Engineering Conference collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference*. American Society of Mechanical Engineers, 2014, pp. V001T04A043–V001T04A043.

[13] S. Feng, Y. Zhang, Q. Chen, C. Zuo, R. Li, and G. Shen, "General solution for high dynamic range three-dimensional shape measurement using the fringe projection technique," *Optics and Lasers in Engineering*, vol. 59, pp. 56–71, 2014.

[14] S. Zhang and S.-T. Yau, "High-resolution, real-time 3D absolute coordinate measurement based on a phase-shifting method," *Optics Express*, vol. 14, no. 7, pp. 2644–2649, 2006.

[15] D. Malacara, *Optical shop testing*. John Wiley & Sons, 2007, vol. 59.

[16] Z. Li, K. Zhong, Y. F. Li, X. Zhou, and Y. Shi, "Multiview phase shifting: a full-resolution and high-speed 3D measurement framework for arbitrary shape dynamic objects," *Optics letters*, vol. 38, no. 9, pp. 1389–1391, 2013.

[17] Z. Li, Y. Shi, and C. Wang, "Research on structured light 3D measuring technology and system based on digital fringe projection(in Chinese)," Ph.D. dissertation, Huazhong University of Science and Technology, 2009.

[18] Y. K. JIANG and C.-s. G. Jin-yue, "Fitting to multi-peak data by least square method and calculating center position of multi-peak curves," *Physics Experimentation*, vol. 11, p. 012, 2003.