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Dynamic Focal Spots Registration Algorithm for Freeform Surface Measurement

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ABSTRACT

In a wavefront sensing system, the raw data for surface reconstruction, either the slope matrix or curvature matrix, is obtained through centroiding on the focal spot images. Centroiding is to calculate the first moment within a certain area of interest, which encloses the focal spot. As the distribution of focal spots is correlated to the surface sampling condition, while a uniform rectangular grid is good enough to register all the focal spots of a uniformly sampled near flat surface, the focal spots of aspherical or freeform surfaces have varying shapes and sizes depending on the surface geometry. In this case, the normal registration method is not applicable. This paper proposed a dynamic focal spots registration algorithm to automatically analyze the image, identify and register every focal spot for centroiding at one go. Through experiment on a freeform surface with polynomial coefficients up to 10th order, the feasibility and effectiveness of the proposed algorithm is proved

Keywords: wavefront sensing system, centroiding, focal spots registration, freeform surface measurement

1. INTRODUCTION

Freeform surfaces are increasingly used in the industry and in various applications due to their advantages such as reduced geometrical aberrations, reduced complexity, reduced system size and weight, and greater design flexibility¹. Such surfaces are a challenge to manufacture and to measure, and meanwhile their function is by definition profoundly affected by their geometrical characteristics. The non-contact freeform surface measurement is therefore badly demanded².

1.1 Wavefront sensing systems for freeform surface measurements

Compared to other non-contact optical surface measurement techniques, including interferometry, confocal microscopy and moiré fringe projection, wavefront sensing technique can achieve height accuracy within the nano scale³, while being insensitive to vibration, no need of a coherent light source, and having extendable dynamic range, which are issues in interferometry⁴. As such, wavefront sensing is promising for applications in freeform surface measurements compared to other non-contact optical surface measurement techniques.

A wavefront sensing system uses a lenslet array to focus the incoming wavefront, which is reflected from the sample surface, onto a CCD, as shown in Fig. 1. The centroid displacement of a focal spot from a reference location is related to the slope, or curvature, of the wavefront sampled by the corresponding lenslet. The form of the sample surface is revealed after reconstruction. From the working principle, the measured raw data is the centroid positions of the sampled focal spots.

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Figure 1. Working principle of the wavefront sensing technique.

1.2 Focal spots registration

The centroid position of each focal spot is calculated by evaluating the first moment within its surrounding area. As such, the first step to process the received image is to sample it by registering clusters of pixels, which are identified as focal spots, into respective area. The basic requirement for the area is to enclose the focal spot completely, without including pixels belong to neighboring focal spots. The distribution of focal spots is correlated to the surface sampling condition; therefore, the area to register each focal spot on the image is correlated to the surface sampling condition as well.

The traditional focal spot registration method defines a uniform rectangular grid. This method is straight-forward, but needs the estimation of offset value and area size, which may involve several rounds of try and error. Also, it is rigid in terms of shape and size.

For a uniformly sampled near flat surface, the focal spots are relatively evenly distributed as illustrated in Fig. 2a. For such kind of images, a uniform rectangular grid is good enough to register all the focal spots, as shown in Fig. 2b.

Figure 2. Image of a reference plane mirror (a) before focal spots registration and (b) with focal spots registration.

For an aspherical or freeform surface, the focal spots have varying shapes and sizes depending on the surface geometry, especially when the spots are not well focused. For example, a freeform surface with polynomial coefficients up to 10^{th} order, as shown in Fig. 3, generates a focal spot image as shown in Fig. 4. The corresponding areas to register the focal

spots need to have varying shapes and sizes to meet the basic criteria. For such kind of images, the traditional registration method is difficult or even impossible to be applied. Sometimes, it is necessary to register focal spots area by area, as illustrated in Fig. 5. This tedious process is not only time consuming, but also vulnerable to operational error.

Figure 3. A freeform sample with polynomial coefficients up to 10th order.

Figure 4. Focal spot image of a freeform sample.

Figure 5. Illustration of applying the traditional focal spots registration method on the image of a freeform sample.

Due to the characteristics of freeform surfaces, a more elegant algorithm that can automatically analyze the image, identify and register focal spots for every sampled area on the surface at one go is desired. So far, no research work on this topic is reported.

2. DYNAMIC FOCAL SPOTS REGISTRATION ALGORITHM

2.1 Challenges

Normally, a freeform surface is measured in a digital wavefront sensing system⁵. The use of the spatial light modulator (SLM) as a flexible lenslet array to better focus a wavefront with varying curvatures increases the noise due to the zero and high order diffraction, as shown in Fig. 6. Also, the image may have background noise that muddled the distinguishability of the focal spots, as shown in Fig. 7. Therefore, besides being able to register focal spots of varying shapes and sizes corresponding to the sample geometry, the algorithm must also be capable of identifying diffraction spots from real focal spots, while being insensitive to the background noise.

Figure 6. Illustration of diffraction spots in a digital wavefront sensing system.

Figure 7. Illustration of background noise.

2.2 Dynamic focal spots registration algorithm

This paper proposes a dynamic focal spots registration algorithm for freeform surface measurements. The steps of the algorithm are illustrated by the flowchart as shown in Fig 8.

Figure 8. Flowchart of the dynamic focal spots registration algorithm.

The algorithm firstly re-calculates the intensity at each pixel by averaging with its surrounding pixels. This step helps to remove noise inside each focal spot, as demonstrated in Fig. 9. Then, registration of clusters is conducted with the following sub steps: set a high threshold value, followed by digitize the image. Only clusters bigger than the minimum spot size, which is pre-estimated, are registered. This filtering step removes random noise outside each cluster, such as abnormal pixels caused by contamination. If the number of clusters is less than desired, the threshold value is reduced and the digitization and the cluster registration steps are repeated until the number of clusters is sufficient. Each cluster then forms an area with a unique size based on the number of “1” pixels present. For neighboring clusters with distance smaller than the minimum distance between neighboring spots, which is also pre-estimated, one of them will be identified as a noisy spot depending on the distances with other neighboring spots. After these processes, valid spots of varying shapes and sizes can be identified and registered.

Figure 9. Demonstration of removal of noise inside each focal spot through averaging.

From the above description, variables need to be pre-defined are:

- a. Total number of focal spots to register. This value affects the final number of focal spots registered. The exact number is also affected by the thresholding step.
- b. Threshold reducing gradient. This value determines the speed of the algorithm and how close the final number of registered focal spots approaches the initially defined number. While a small value results in slow speed and a closer number of registered focal spots as desired, a big value results in fast speed but a number of registered focal spots with a relatively large difference as desired. Nevertheless, it has no effect on the shape and size of the area to register the focal spot, once it has been identified.

Variables that need to be pre-estimated are:

- a. Minimum spot size. This value is used for removal of random noise outside each spot.
- b. Minimum distance between neighboring spots. This value is used for exclusion of diffraction spots.

As these two variables are used for differentiating noisy signals from real signals and make focal spots registration feasible in the presence of various noises, it is comparatively important to estimate their values accurately within a certain range. If they deviate significantly from the real values, noisy pixels may be identified as a focal spot and then registered into a corresponding area.

2.3 Experiment

The image of a freeform sample, as shown in Fig. 4, is tested with the proposed dynamic focal spots registration algorithm. With the input total number of focal spots set as 150, Threshold reducing gradient 0.01, minimum spot size of radius 3 pixels, minimum distance between neighboring spots as 35 pixels, the image after applying the proposed dynamic focal spots registration algorithm is shown in Fig. 10. The reconstructed surface is shown in Fig. 11. As compared to the stylus measurement, the RMS error is $0.161\mu\text{m}$. Big errors happen at deep slope regions. The accuracy of the reconstructed surface can be further improved by modifying the sampling method, so as to increase image contrast and SNR.

Figure 10. Illustration of applying the proposed dynamic focal spots registration algorithm on the image of the freeform sample.

Figure 11. Reconstructed surface.

Through the experiment, the feasibility and effectiveness of the proposed dynamic focal spots registration algorithm is proved. As demonstrated in Fig. 10, each area is isolated and has a unique size, which best accommodates the enclosed spot. Therefore, the algorithm is highly flexible and automatic.

3. CONCLUSION

For freeform surface measurements, the traditional focal spots registration method, which defines a uniform rectangular grid on the image, is insufficient to register every sampled area at one go. Its rigid working principle makes the registration process tedious and troublesome. This paper proposes a dynamic algorithm, which does the focal spots

registration for every sampled area independently. The shape and size of each individual area best suits its enclosed focal spot. Experiment verification has proven the feasibility and high flexibility of the proposed dynamic focal spots registration algorithm. As such, focal spots registration for the image of a freeform surface at one go is possible.

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