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Toroidal surface measurement with elliptical lenslet array

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ABSTRACT

Toroidal surfaces have wide applications in optics and manufacturing industry. Due to the strong aspherical surface profile of a toroidal surface, there are few optical measurement techniques proposed or reported for its measurement. This paper proposed digital Shack Hartmann wavefront sensor (SHWS) with extendable dynamic range. Instead of the traditional spherical lenslet array, which cannot sample the wavefront in two directions simultaneously, an elliptical lenslet array realized by a spatial light modulator (SLM), which provides different optical powers in two directions, is used in the system. With the incorporation of the extended version of the traditional SHWS, the reference-free wavefront sensor (RFWS), curvature matrix is measured, which can be further reconstructed into the surface profile. Both numerical simulation and experimental study has been conducted and the feasibility of measuring toroidal surfaces in the RFWS system with an elliptical lenslet array is proven.

Keywords: Toroidal surface measurement, Shack-Hartmann wavefront sensor, reference-free wavefront sensor, elliptical lenslet array

1. INTRODUCTION

Toroidal surfaces have wide applications in optics and manufacturing industry¹. It is of high importance to evaluate the surface form for good mechanical design and high quality control². Due to the strongly aspherical surface profile of a toroidal surface, especially its non-rotationally symmetrical feature, there are few optical measurement techniques proposed or reported for its measurement. This paper proposes to use the Shack-Hartmann wavefront sensor (SHWS) for measuring such kind of surfaces because of its extendable dynamic range as compared to interferometry.

1.1 SHWS

In an SHWS system, a lenslet array is used to focus the incoming wavefront onto a CCD (Fig. 1). The centroid locations of the focal points are compared with those of the reference focal points. The displacement of each centroid location reflects the wavefront slope (Fig. 2)³. In a typical SHWS system, the lenslet array is made up of spherical microlenses. In this project, a spatial light modulator (SLM) is used to replace the physical one in a traditional SHWS setup for its programmable capability⁴.

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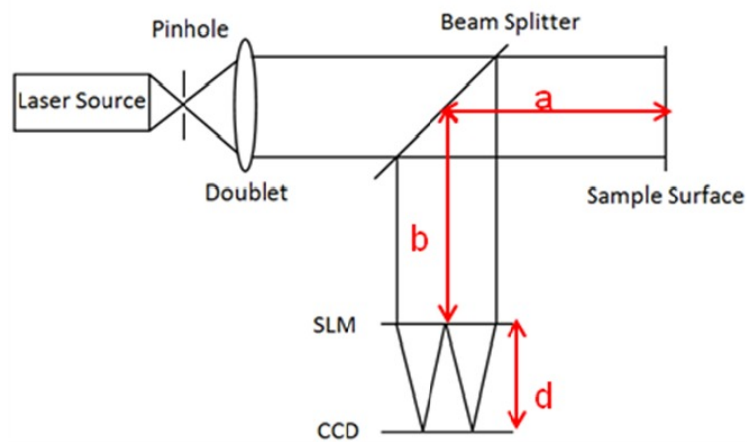


Figure 1. The typical SHWS system setup.

1.2 Challenges in using SHWS for toroidal surface measurements

From the working principle of the SHWS, the lenslet array samples the incoming wavefront reflected back from the sample surface, and forms individual focal spots on the detector plane. However, due to the different curvatures in two perpendicular dimensions of a toroidal surface, it is impossible to sample the wavefront in two directions simultaneously with the normal lenslet array⁵.

For example, a toroidal sample with the design parameters listed in Table 1 is measured in a traditional SHWS system, with focal length of 50mm. The captured spots image is shown in Fig. 2.

Table 1. Specifications of the sample toroidal surface.

L_x (mm)	L_y (mm)	R_x (mm)	Surf	R_y (mm)	R_x/R_y
50	50	245.4	276.6	Concave	0.887

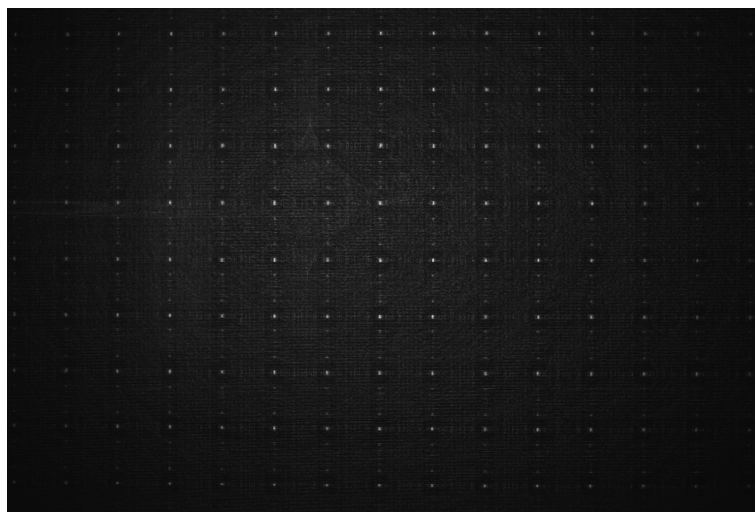


Figure 2. Spot image captured with a normal lenslet array.

Another main challenge in toroidal surface measurement is to the availability of a proper reference piece to generate the reference focal points. Without this information, the slope matrix cannot be obtained⁶.

2. TOROIDAL SURFACE MEASUREMENT WITH ELLIPTICAL LENSLET ARRAY

2.1 Elliptical lenslet array design

With the great flexibility provided by the SLM, various parameters of the designed lenslet array can be easily adjusted. Elliptical lenslets provide different optical powers in two directions⁵. When the parameters are designed properly, this kind of digital SHWS can sample the wavefront of a toroidal surface properly. For a toroidal surface with radii in two directions labeled as R_x and R_y , when the distance between the sample and the SLM is represented by $(a+b)$ and the light beam is well-collimated, the radii of the reflected wavefront present at the SLM can be approximated as

$$R_{SLM} = \frac{R_{Sample}}{2} - (a + b) . \quad (1)$$

If the focal length of the elliptical lenslet along the x direction is designed as f_x , the effective focal distance is calculated as

$$f_x^{Sample-SLM} = R_x^{SLM} , \quad (2)$$

$$\frac{1}{f_{eff}} = \frac{1}{f_x} + \frac{1}{f_x^{Sample-SLM}} . \quad (3)$$

The focal length of the elliptical lenslet along the y direction is then calculated as

$$f_y^{Sample-SLM} = R_y^{SLM} , \quad (4)$$

$$\frac{1}{f_{eff}} = \frac{1}{f_y} + \frac{1}{f_y^{Sample-SLM}} . \quad (5)$$

Take the toroidal surface with the specifications listed in Table 1 as an example. If the focal length of the elliptical lenslet along the x direction is designed to be 50mm, the distance between the sample and the SLM, or $(a+b)$, is set at 225mm, the effective focal distance is calculated as 97.8011mm, and the focal length along the y direction should be 45.9583mm. With these parameters, the captured spots image is shown in Fig. 3. The improvement in the spots quality is illustrated in Fig. 4. The two figures show the captured spots at the same sampling position, but one with a spherical lenslet and the other with an elliptical lenslet. While the spot sampled by a spherical lenslet is elongated along one direction and is not so well focused, the one sampled by the elliptical lenslet is relatively more concentrated. Through the implementation of elliptical lenslets, toroidal surfaces can be well sampled.

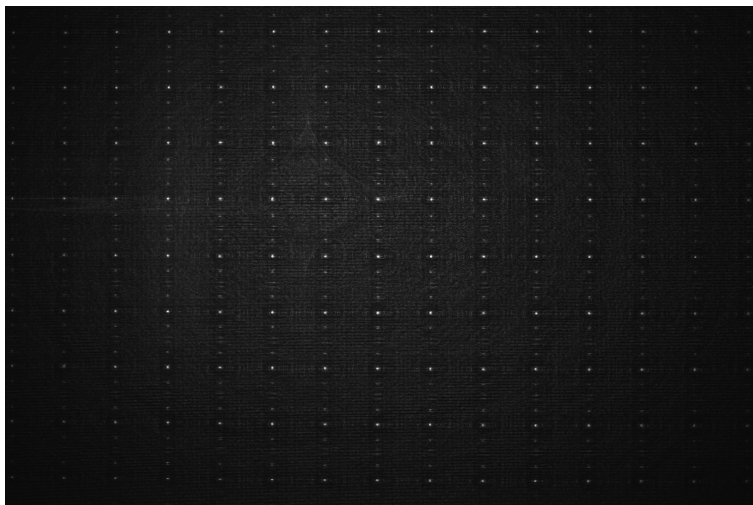


Figure 3. Spot image captured with the elliptical lenslet array.

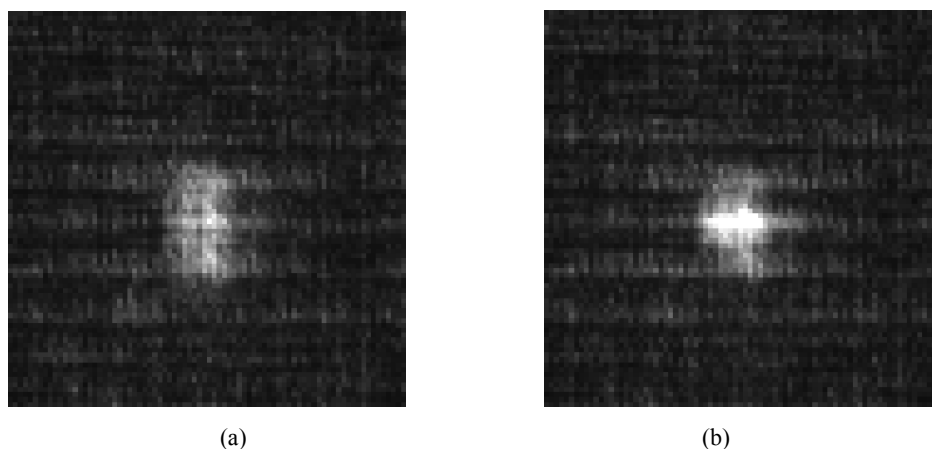


Figure 4. Spot sampled by (a) spherical lenslet, and (b) elliptical lenslet array.

2.2 Toroidal surface measurement in the digital RFWS system with elliptical lenslet array

The reference issue can be tackled in the extended version of the traditional SHWS, the reference-free wavefront sensor (RFWS), which measures wavefront curvature without involving a reference piece by comparing the images of the sample before and after a lateral shift⁶. Theoretically, incorporating the elliptical lenslet array concept as described in the previous session into an RFWS, the curvature matrix of a toroidal surface should be able to be obtained, which can be further reconstructed into surface form.

2.3 Simulation

A toroidal surface with the specifications as listed in Table 1 is simulated in the RFWS system with elliptical lenslet array. The distance between the sample and the SLM is set at 225mm; the elliptical lenslet array has the same specifications as described in Session 2.1. The final reconstructed surface is shown in Fig. 5. While the peak-valley (PV) value is 0.441mm, the RMS error (RMSE) of the reconstructed surface is 14.3nm. The reconstructed surface with a spherical lenslet array is shown in Fig. 6 for comparison. The focal length at both directions is set to be 50mm. The

RMSE of the reconstructed surface from a spherical lenslet measurement is calculated to be $0.1091\mu\text{m}$. The simulation result demonstrates the feasibility of the proposed technique.

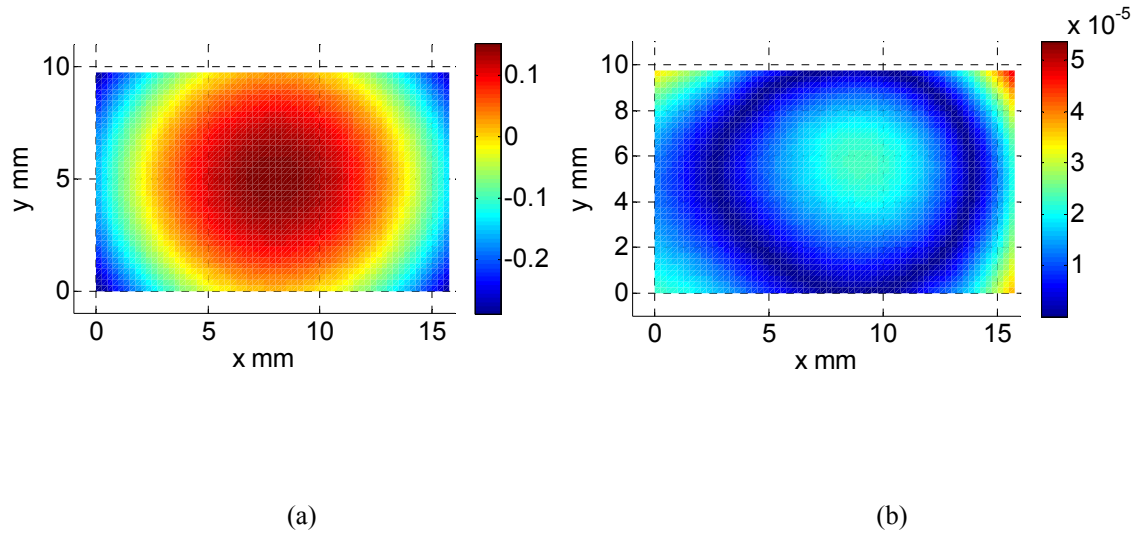


Figure 5. (a) Reconstructed surface of the toroidal sample from an elliptical lenslet measurement, and (b) corresponding error map as compared to the nominal surface.

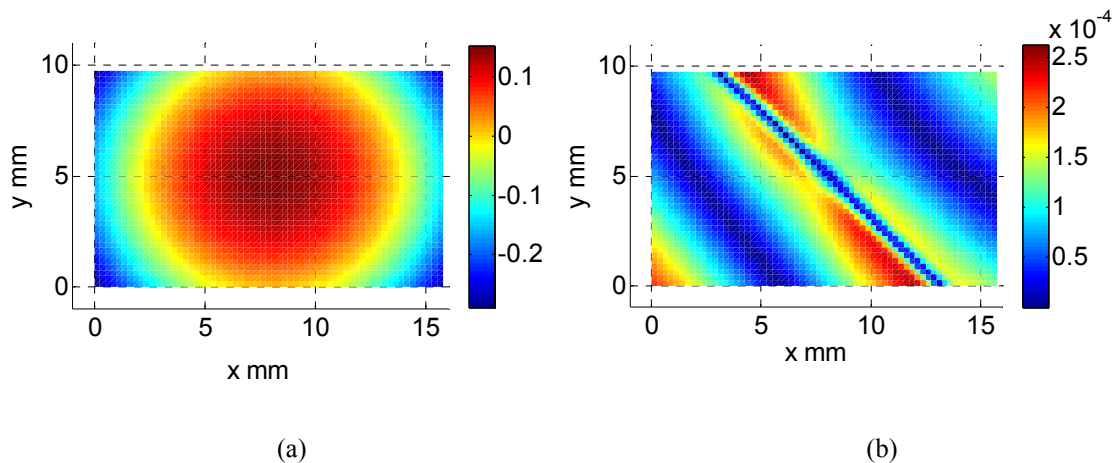


Figure 6. (a) Reconstructed surface of the toroidal sample from a spherical lenslet measurement, and (b) corresponding error map as compared to the nominal surface.

2.4 Experiment

To verify the feasibility of the proposed system, a digital RFWS system as shown in Fig. 7 was built up. The SLM is Holoeye transmissive LC2002, with a pixel size of $32\mu\text{m}^2$. The same toroidal sample as used in the simulation is measured. The distance between the sample and CCD was measured to be 225mm, thus the elliptical lenslet array design is the same as used in the simulation. The final reconstructed surface is shown in Fig. 8. The RMS error (RMSE) is

calculated to be 82.7nm. The reconstructed surface with a spherical lenslet array is shown in Fig. 9 for comparison. With a spherical lenslet of focal length 50mm, the RMSE is calculated to be 0.854 μ m. The feasibility of the proposed technique to measure toroidal surfaces is proven experimentally.

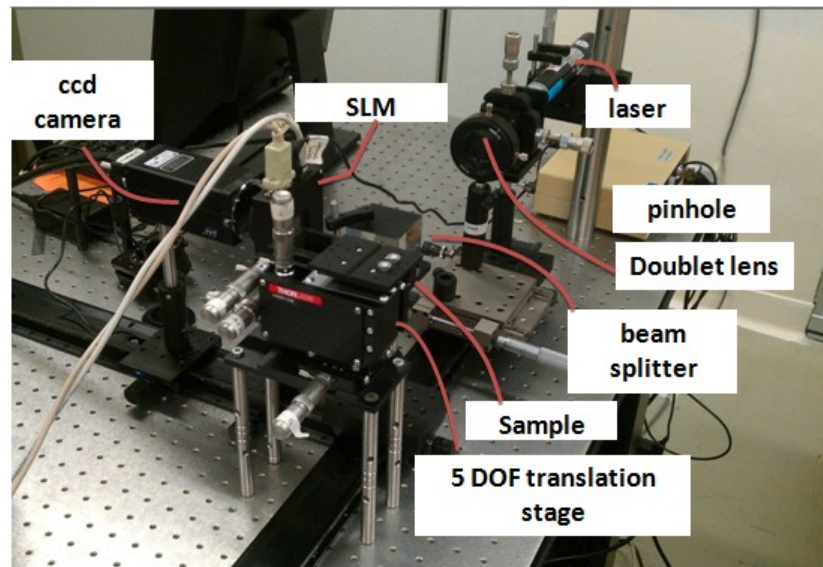


Figure 7. Experiment setup.

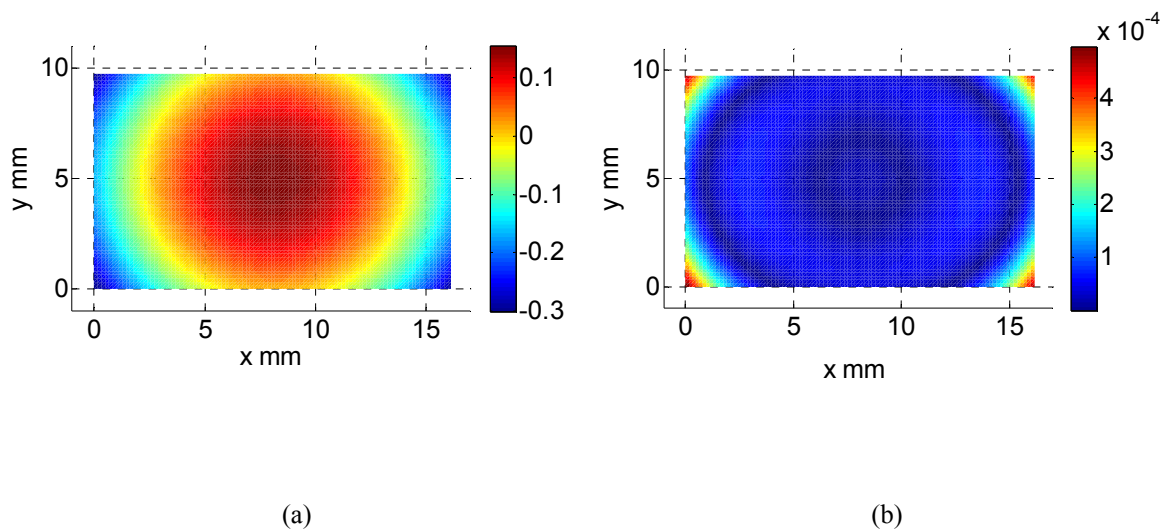


Figure 8. (a) Reconstructed surface of the toroidal sample from an elliptical lenslet measurement, and (b) corresponding error map as compared to the nominal surface. (PV=0.4574mm)

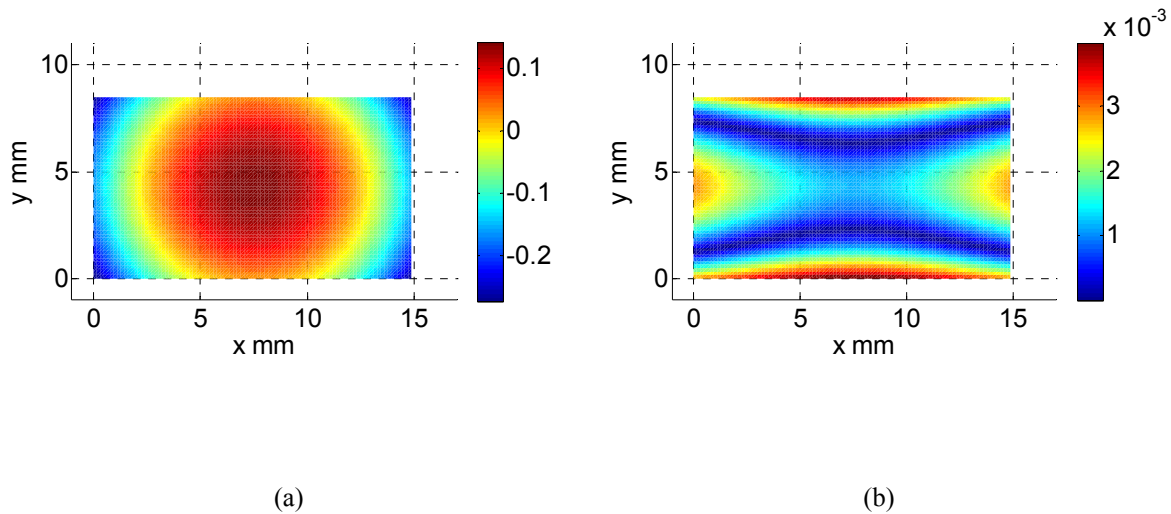


Figure 9. (a) Reconstructed surface of the toroidal sample from a spherical lenslet measurement, and (b) corresponding error map as compared to the nominal surface. (PV=0.418mm)

3. CONCLUSION

The traditional spherical lenslet array cannot sample a toroidal surface simultaneously due to its different radius in two perpendicular directions. Also, the lack of a proper reference makes obtaining the slope matrix impossible. This paper proposed to use the elliptical lenslet array realized by SLM in the RFWS system. With a proper sampling and measuring the curvature matrix, toroidal surfaces can be measured. Both numerical simulation and experiment have been conducted on a toroidal surface with a radius ratio of 0.887 to verify the feasibility of the proposed system. While the RMSE of $0.1091\mu\text{m}$ from simulation and $0.854\mu\text{m}$ from experiment with a spherical lenslet as the sampling aperture; the RMSE of 14.3nm from simulation and 82.7nm from experiment with an elliptical lenslet array proved that toroidal surfaces can be successfully measured in the proposed system.

4. ACKNOWLEDGEMENT

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