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Optimization of scanning strategy of digital Shack–Hartmann wavefront sensing

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In the traditional Shack–Hartmann wavefront sensing (SHWS) system, a lenslet array with a bigger configuration is desired to achieve a higher lateral resolution. However, practical implementation limits the configuration and this parameter is contradicted with the measurement range. We have proposed a digital scanning technique by making use of the high flexibility of a spatial light modulator to sample the reflected wavefront [X. Li, L. P. Zhao, Z. P. Fang, and C. S. Tan, “Improve lateral resolution in wavefront sensing with digital scanning technique,” in Asia-Pacific Conference of Transducers and Micro-Nano Technology (2006)]. The lenslet array pattern is programmed to laterally scan the whole aperture. In this paper, the methodology to optimize the scanning step for the purpose of form measurement is proposed. The correctness and effectiveness are demonstrated in numerical simulation and experimental investigation. © 2011 Optical Society of America

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1. Introduction

Within a certain area to be measured, the more sampling points, the better the lateral resolution. In the Shack–Hartmann wavefront sensing (SHWS) system, each local sampling aperture acts like an optical probe. The probe array samples the surface and each probe carries the information of the surface’s respective local area. In order to generate more sampling points so as to increase the lateral resolution, more probes are desired to sample a surface. However, due to the following reasons, there is a limitation to the maximum number of lenslets that can be used in a system. First of all, an increase in the number of probes indicates a decrease in the diameter of each lenslet. However, the size of the lenslet cannot be reduced infinitely due to engineering capability. Secondly, the accuracy of SHWS is affected by the focal spot centroid finding process [1]. Generally speaking,

for a fixed focal length, the bigger the lenslet diameter, the smaller the focal spot and thus higher the sensor accuracy [2]. As such, it is desired to increase the diameter of the lenslet, so as to reduce the spot size. Thirdly, large focusing spots have a higher chance of overlapping each other, which makes correlation of each spot with its corresponding lenslet ambiguous [3]. Therefore, it is also desired to increase the diameter of the lenslet for a fixed focal length, so as to increase the dynamic range of the sensor. Last but not least, when the SHWS is applied to measure a highly aberrated wavefront, the number of lenslets is further limited so as to provide a large dynamic range [4]. In other words, crosstalk is more likely to happen when the number of focal spots is large [5], which makes correct registration of each spot impossible. Therefore, there is a contradiction between the high lateral resolution achieved by increasing the number of lenslets and measurement range. Scanning is thus proposed in a lot of research work to increase the lateral resolution without physically enlarging the aperture configuration.

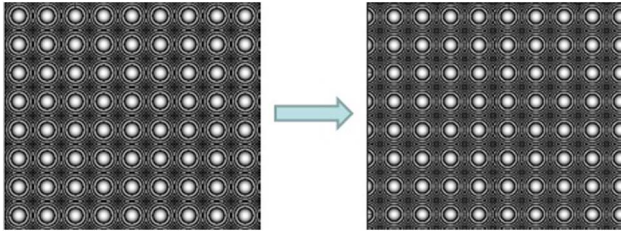


Fig. 1. (Color online) Digital scanning of the lenslet array realized by a spatial light modulator.

We have proposed a digital scanning SHWS [6]. A spatial light modulator (SLM) is used as the sampling aperture [7,8]. The lenslet array pattern is programmed to shift in the lateral direction (Fig. 1). After the scanning is done, the images obtained are stacked together along the scanning direction for further processing. Wavefront reconstruction is then applied on this resultant compiled image.

2. Optimization of Scanning Step

A. Simulation

For surface form measurement, the roughness information, which is of high frequency, is not of interest. Therefore, it is not necessary to have the most sampling points as the whole process is time-consuming and risks vibration-related errors. In this paper, we are seeking the optimum setting for efficient precision form measurement, where a reasonable number of sampling points with scanning is of primary concern. The optimum scanning step is reached where the form accuracy achieved at this value is within error tolerance and beyond which the accuracy improved can be considered as insignificant.

Simulation has been conducted to explore how to optimize the scanning step and find this value in various surface measurements. The surfaces are simplified to be 2D curves that are varying along the x direction only, with the forms described by $\varphi = A \sin(\omega x)$. Assume $A = 10$, which means that the maximum height discrepancy over a flat is $10 \mu\text{m}$. In consideration of possible occurrence of crosstalk, we examine surfaces with spatial frequencies in terms of the number of waves over the length of 16 mm to be 0.25, 0.5, 1, 1.5, and 2. The focal length of each lenslet is fixed at 100 mm. To align the simulation platform with the actual experiment setup, we studied the lenslet array patterns with different settings detailed in Table 1.

In this study, the optimum scanning step is the value at which the RMS measurement error, ϵ_{ms} , of the absolute height of the reconstructed wavefront compared with the simulated surface deviates within

10% of the value that can be achieved at the maximum number of sampling points, where the minimum ϵ_{ms} is obtained. In the experiment, the maximum number of sampling points is set to be 900; this value is achieved by a scanning interval of 0.016 mm. In other words, when ϵ_{ms} reduces to 110% of the minimum ϵ_{ms} , the corresponding scanning step is considered as optimum. The ϵ_{ms} values thus resulted in a various number of sampling points that use different lenslet settings and are plotted in Fig. 2. From Fig. 2, we can conclude the following findings.

a. For a fixed lenslet size, the measurement error decreases as the number of sampling points increases, regardless of the form of the surface to be measured. However, the improvement in accuracy slows down with the increasing of the scanning steps and the improved accuracy closes to a fixed level for a particular lenslet, which is higher for smaller lenslets and lower for bigger lenslets.

b. For measuring surfaces with different spatial frequency, the ϵ_{ms} will be different. When the spatial frequency is higher, the corresponding error will be bigger. In measuring a surface, the improvement in accuracy through scanning is confined to a certain level, beyond which it is necessary to reduce the lenslet size.

As discussed above, the optimum scanning step is obtained where ϵ_{ms} reduces to 10% above the measurement error when the scanning interval is 0.016 mm. Hence, in Fig. 2, for each series of data, the horizontal value when the vertical value reduces to its respective $1.1 \times \min \epsilon_{\text{ms}}$ is taken down and this is the optimum number of sampling points in that particular scenario. The average value of the thus determined optimum number of sampling points for each lenslet setting when measuring different surfaces and the corresponding standard deviation are detailed in Table 2. The maximum standard deviation is 1.3; we thus adopt the average value to be the optimum number of sampling points for that particular lenslet setting. The optimized scanning step for different lenslets is thus calculated and listed in Table 2 as well.

From this study, we find that after four times scanning, the reconstructed wavefront is very much the same as the form obtained after the most possible scanning steps conducted. More scanning beyond this value will give little improvement in ϵ_{ms} . However, we need to take note that, although the optimum scanning step for various lenslet diameters is the same, the measurement accuracy is different when the size of the lenslet is different. For example, when the lenslet diameter is 4.8 mm and the surface to be measured contains two waves, through optimization, the ϵ_{ms} is $7.55 \mu\text{m}$ at the optimum scanning step 4. Under the same condition, if the lenslet diameter reduces to 0.96 mm, the ϵ_{ms} will be $0.24 \mu\text{m}$.

Therefore, as the accuracy of the Shack–Hartmann system is intrinsically determined by the lenslet setting, it is the first step to properly choose a suitable lenslet size based on the error budget. Scanning can

Table 1. Various Lenslet Array Settings

Lenslet diameter (mm)	0.96	1.44	1.6	2.4	2.88	4.8
Lenslets per image (along the x direction only)	15	10	9	6	5	3

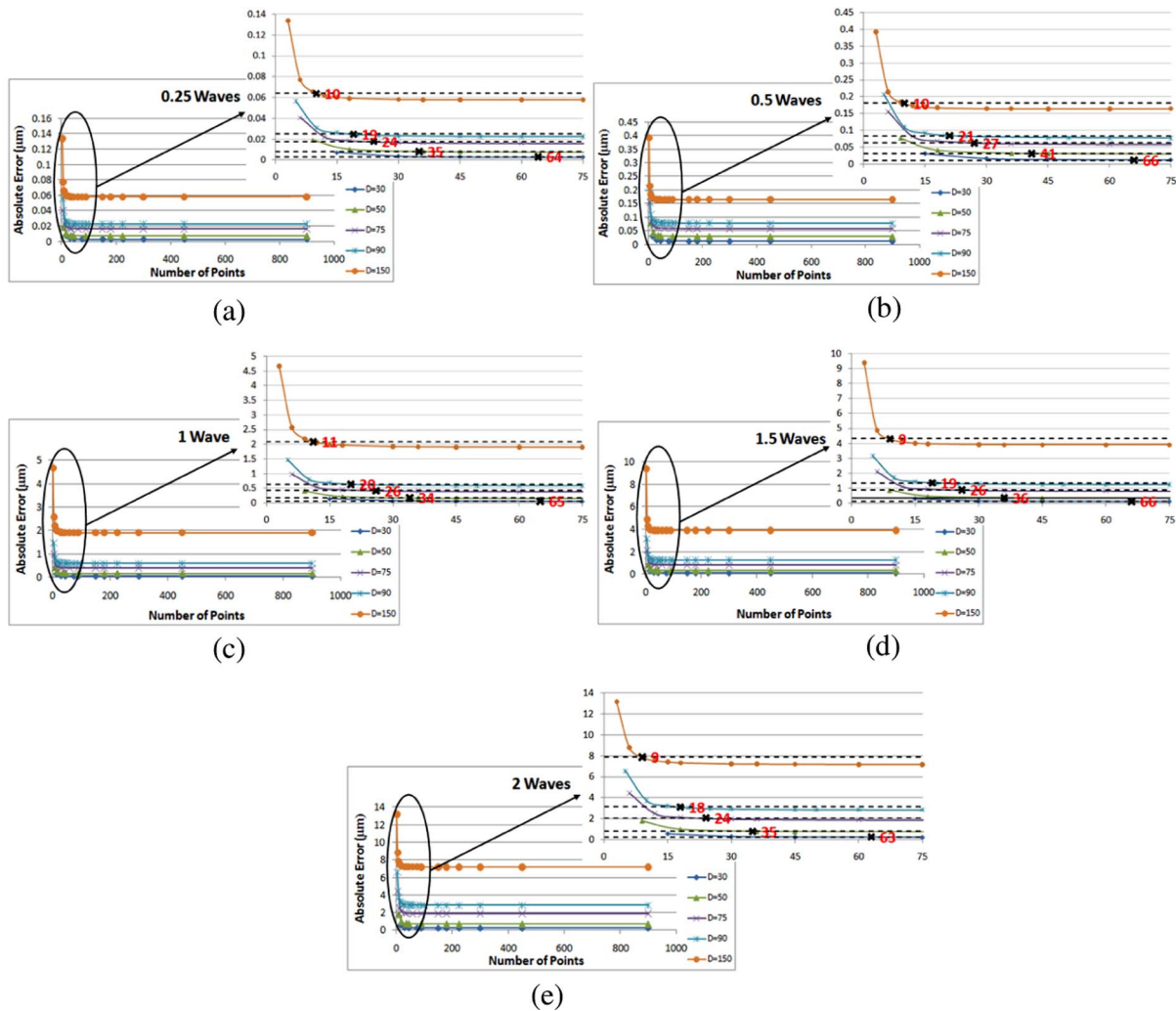


Fig. 2. (Color online) ϵ_{ms} for different lenslet sizes and different number of points in various surface measurement scenarios, as the number of waves is (a) 0.25; (b) 0.5; (c) 1; (d) 1.5; and (e) 2.

help to improve the lateral resolution, but the improvement in performance is limited by the maximum level of the lenslet array. In the scenarios that we have studied, in terms of the efficiency and feasibility of practical implementation, a four-step scanning is sufficient to reach submicron ϵ_{ms} with a spatial frequency as high as 0.125 mm^{-1} .

B. Experiment

Two one-dimensional surfaces (form varying along one direction only) with different peak-valley (PV) value and different spatial frequency have been measured to verify the proposed optimization methodology (Fig. 3). The SLM used in the system is Holoeye LC2002, having 800×600 pixels in total, with a pixel size of $32 \text{ } \mu\text{m}$. The CCD is Basler A501k, having

1280×1024 pixels, with a pixel size of $12 \text{ } \mu\text{m}$. The sample area is $16 \times 16 \text{ mm}^2$. The lenslet diameter is set to be 1.6 mm with corresponding optimum scanning steps of four as obtained from the simulation study. The aberration of the sampling aperture is measured to be $0.0453 \text{ } \mu\text{m}$, with a standard deviation of $0.0233 \text{ } \mu\text{m}$. The surfaces reconstructed from 900 sampling points along the x direction (100 scanning steps) are plotted in Fig. 4a and Fig. 4c, respectively. The average of the results along the y direction is calculated for analysis. These averaged results (with “.” marker), which are treated as the base curve to be compared with, are plotted together with the averaged results of wavefront reconstructed from 36 sampling points (four scanning steps, with “☆” marker), 450 sampling points (50 scanning steps,

Table 2. Summary of the Optimum Scanning Steps for Various Lenslet Sizes

Lenslet diameter (mm)	0.96	1.44	1.6	2.4	2.88	4.8
Average optimum number of sampling points	65.0	42.9	35.8	25.0	18.9	9.7
Standard deviation	1.3	1.2	0.5	1.0	0.7	1.2
Optimum scanning step	4	4	4	4	4	4

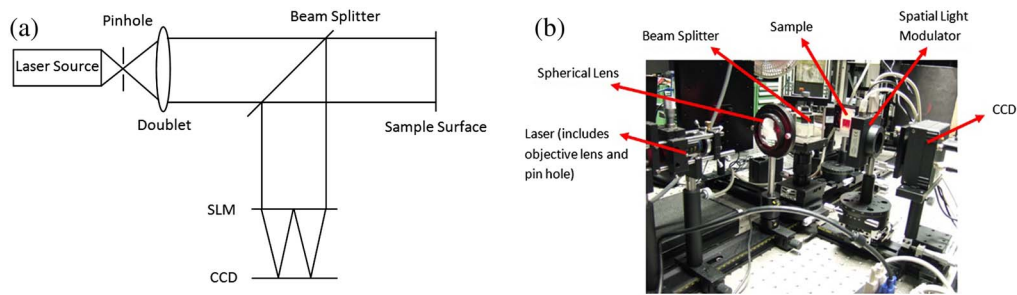


Fig. 3. (Color online) Experiment setup, as (a) sketch (b) image of the real setup.

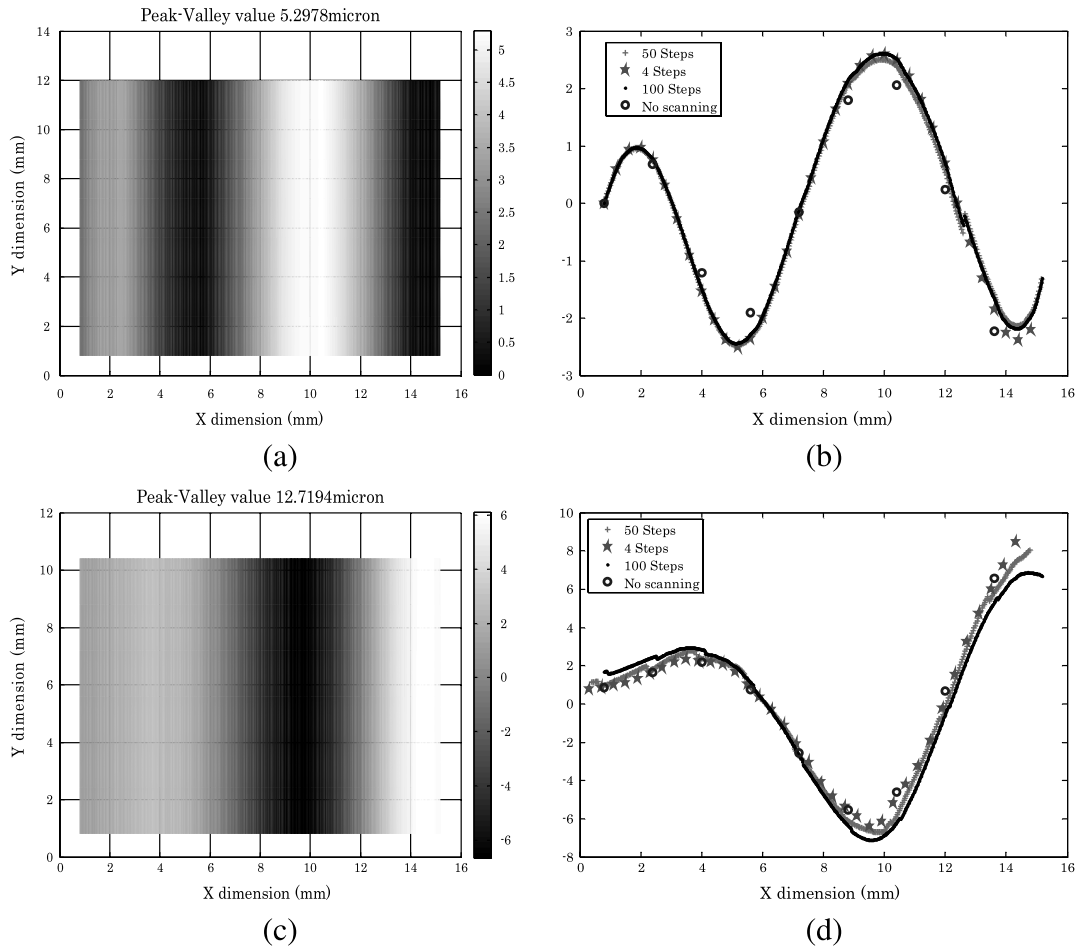


Fig. 4. Experiment results, as (a and c) surface reconstructed from 900 sampling points; (b and d) averaged reconstructed wavefront along the form varying direction for various scanning steps.

with “+” marker), and nine sampling points (no scanning, with “O” marker) [Fig. 4b and Fig. 4d]. From the results, we observe that when no scanning

is done, the reconstructed surface profiles deviate significantly from the base curves. After four-step scanning or 50-step scanning, the reconstructed

Table 3. Relative ϵ_{ms} Resulted at Various Scanning Steps and the Improvement in Accuracy through Increasing Scanning Steps

Scanning steps		0	4	50
Surface as shown in Fig. 3a and Fig. 3b	Relative ϵ_{ms} (μm)	0.33	0.146	0.066
	Improvement (%)		55.5	55.5
Surface as shown in Fig. 3c and Fig. 3d	Relative ϵ_{ms} (μm)	0.8548	0.7231	0.631
	Improvement (%)		15.5	12.7

surface profiles align well with the base curves. The corresponding ε_{ms} , as compared to the value at 100-step scanning, are listed in Table 3. From the table, after conducting a four-step scanning, the ε_{ms} has been effectively reduced. Certainly, if the error budget is set at a different level, this optimum scanning step needs to be calculated again based on this optimization methodology.

3. Conclusion

In conclusion, we have proposed a digital Shack-Hartmann wavefront scanning to increase the lateral resolution without compromising the sensitivity or dynamic range. Through simulation and measurement of two 2D surfaces with different PV values and different spatial frequencies, we demonstrated that, by optimization of the scanning step, the measurement performance can be improved significantly with practically feasible minimum effort. Although in the scenarios we studied, the optimized scanning steps are the same, which is four to be particular, we need to take note that the level of accuracy in each scenario is different due to the intrinsic error brought on by the size of the lenslet in measuring various surface forms. Therefore, we need to choose the suitable lenslet diameter before we proceed to scanning in order to achieve its practically optimum accuracy level.

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