Simulation of the sensing performance of a Shack-Hartmann wavefront sensor related to the lenslet array

Wenjiang Guo\textsuperscript{a,b,\ast}, Liping Zhao\textsuperscript{b}, I-Ming Chen\textsuperscript{a}

\textsuperscript{a}Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
\textsuperscript{b}Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075, Singapore

Abstract

A Shack-Hartmann wavefront sensor (SHWS) uses a lenslet array to sample incoming wavefront onto a CCD. By comparing the focal spots images of the sample and a reference, wavefront profile is reconstructed and therefore the sample shape is revealed. Various factors affect the performance of SHWS. In order to study how and to which extend does each factor affect the reconstruction result, we established a simulation platform in MATLAB. Detailed properties, especially the configuration of the lenslet array related issues, were analyzed through this system-oriented platform, and by doing so we obtained some guidance in surface measurement experiment.

Keywords: Shack-Hartmann wavefront sensor; lenslet array; configuration; simulation; sensing performance

1. Introduction

Shack Hartmann Wavefront Sensor (SHWS) was invented in 1971 [1]. The main component of a SHWS is a lenslet array, which is usually simplified as an array of plano-convex lenses of the same focal length (Fig. 1 [2]). The lenslet array focuses incoming wavefront onto a Charge-Coupled Device (CCD). The focal spots at CCD are compared with reference spots. Phase aberration is then reconstructed based on the displacement of the centroid position of each focal spot. Reference spots are generated when incoming wavefront comes from surfaces with known profile, normally in the form of a perfectly flat mirror. When wavefront is not flat, tilt in incoming wavefront will happen, and that leads to a shift of focal spots’ locations. Therefore, by measuring displacements of centroids and subsequent use of a wavefront reconstruction algorithm, surface profile can be reconstructed [3].
Although the working principle of SHWS is quite clear, its properties and applications in some areas are still under study and investigation in laboratory. Questions such as the proper kind of sensing light to use, the influence of lenslet array to reconstructed profiles, and the tolerance of CCD position, have not been answered and difficult to study through experiment. Various noises, due to the intrinsic design of the sensor as well as the environment, coexist, and that makes the study of individual factor practically impossible. However, with a virtual SHWS built in MATLAB, it is always easy to isolate each affecting factor and study its influence on the system’s performance. This paper focuses on the configuration of lenslet array.

2. Methodology of SHWS simulation

The signal flow is illustrated in figure 2. The intersection points at CCD are determined by ray tracing. Ideal situation is defined when sensing light is collimated with a uniform distribution, the lenslet array is in close contact with the test surface, and the CCD is exactly at the focal plane. We evaluate the performance by comparing the reconstructed wavefront profile with the designed shape. A MATLAB function, “polyfit”, is used to find the coefficient of the reconstructed surface. Theoretically, due to reflection, this coefficient should be double the value of that for the designed shape. Relative error between the two is used as a quantitative criterion.

3. Lenslet array in SHWS

3.1. Configuration

While keeping other factors at ideal situation, we vary the configuration of the lenslet array. The focal length is always kept at the same value.

For a slanted surface (Fig. 3a), as configuration increases from 4×4 to 32×32, relative error decreases gradually from 0.173% to 0.042%. For a spherical surface (Fig. 3b), as configuration increases from 4×4 to 32×32, relative error decreases gradually from 0.129% to 0.065%.
Fig. 3. Relative error of the reconstructed coefficient for various configurations in the case of (a) slanted surfaces and (b) spherical surfaces.

The reason behind this phenomenon is explained based on the physical model. Each centroid at CCD can be thought as the averaging information from a surface area that is determined by the size of the lenslet. Small configuration results in a large lenslet diameter, which means that each centroid represents the averaging information from a large area. When configuration increases in size, the surface area represented by each centroid decreases, and the ability of each centroid to describe that part of area increases. That is why we can see from the two graphs that error decreases as the number of lenslet increases. We may therefore conclude that the reconstructed wavefront approaches the real shape when configuration increases.

3.2. Measurement range

There is a limit to the peak-valley (PV) value of a surface that a lenslet array is able to sample. Take the lenslet array with configuration of 16×16 as an example. From the plot of intersection points at CCD, we observe that when PV value is small, intersection points are regular and well presented in 16×16 separated blocks clearly (Figure 4a). However, when PV value exceeds a certain number, overlapping of points is about to occur and those intersection points are in bad condition (Figure 4b). This phenomenon is known as crosstalk. If there is crosstalk, in actual application, CCD cannot tell which point corresponds to which lenslet. The misleading of information may cause huge error in the reconstructed result. Therefore, when PV of the test surface is bigger than a certain value, we have to choose another lenslet array with a smaller configuration.

Normally, there are two kinds of measurement range that we are interested in. One is named as principle measurement range (PMR), which denotes the maximum PV value a certain configured lenslet array can measure. The other is called meaningful measurement range (MMR), which is used in the case that the reconstructed results are within a prescribed tolerance. In this platform, we study the MMR for error below 1%. The surface we choose is spherical in shape.

PMR, MMR, and the ratio between the two values are summarized in table 1.

Fig. 4. Intersection points at CCD for (a) PV=0.267 mm and (b) PV= 0.1335 mm. Black dots indicate intersection points of each sampled ray. Red dots indicate the calculated centroids of each block.
<table>
<thead>
<tr>
<th>Configuration</th>
<th>PMR (mm)</th>
<th>MMR (mm)</th>
<th>MMR/PMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4×4</td>
<td>0.3954</td>
<td>0.0687</td>
<td>0.1737</td>
</tr>
<tr>
<td>8×8</td>
<td>0.2929</td>
<td>0.0676</td>
<td>0.231</td>
</tr>
<tr>
<td>16×16</td>
<td>0.267</td>
<td>0.0598</td>
<td>0.2239</td>
</tr>
<tr>
<td>20×20</td>
<td>0.264</td>
<td>0.0596</td>
<td>0.2257</td>
</tr>
<tr>
<td>24×24</td>
<td>0.2605</td>
<td>0.0595</td>
<td>0.2282</td>
</tr>
<tr>
<td>28×28</td>
<td>0.2574</td>
<td>0.0594</td>
<td>0.2309</td>
</tr>
<tr>
<td>36×36</td>
<td>0.2544</td>
<td>0.0597</td>
<td>0.2346</td>
</tr>
</tbody>
</table>

Table 1. Summary of PMR, MMR, and their relative ratio for different configurations.

Figure 5. Summary of (a) PMR and (b) MMR for different configurations.

From this table, we notice that when configuration increases from 4×4 to 36×36, the corresponding PMR decreases gradually from 0.3954 mm to 0.2544 mm (Figure 5a). This is because as the configuration increases, the allowable area that each focal spot can occupy decreases. Thus, crosstalk is more likely to happen. In addition, as we can derive from the physical model, when configuration increases, the non-plano side of the lenslet becomes more convex as the focal length is maintained the same. The shape of the lenslet with big configuration is thus closer to that of the test surface. In such kind of scenario, the lenslet almost loses its converging capability. Therefore, lenslet array with big configuration should have PMR smaller than that of the one with small configuration. This conclusion also applies to MMR (Figure 5b).

Another conclusion we may draw from Table 1 is that although increasing configuration increases accuracy, it is not practical or necessary to always use lenslet array comes with big configuration. If tolerable error is around 1%, for test surfaces with PV value below 0.0687 mm, 4×4 configured lenslet array is good enough to give an acceptable reconstruction result.

4. Conclusion

After detailed study of the SHWS simulation platform, how the configuration of lenslet array affects the system’s performance is clear. Generally speaking, for a surface that has a much small PV value, the accuracy of the reconstructed wavefront increases as configuration increases. However, if the PV value is considerably large, we need to consider the measurement range of the lenslet array. When the PV value of the surface exceeds the lenslet array’s Principle Measurement Range (PMR), we need to change to a lenslet array with a smaller configuration. When the PV value is within the lenslet array’s Meaningful Measurement Range (MMR), it is unnecessary to use a lenslet array with big configuration in order to get a more accurate result.

Configuration is not the only factor of a lenslet array that affects SHWS system’s performance. We will discuss other factors in later publications.

5. Reference