Laser-line scanning speckle reduction based on a one-dimensional beam homogenizer

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ABSTRACT

Laser-line scanners have become ubiquitous in many forms of automation and measurement systems. Despite this fact, these systems are still susceptible to speckle or interference on rough scattering surfaces. Many scanning systems must be calibrated to the material being analyzed to obtain their full potential. In general, post-processing algorithms are used in most modern line-scanning devices in order to smooth out speckle and enhance the resolution through sub-pixel interpolation. However, these post-processing techniques come at a cost of increased CPU time and a subsequent decrease in bandwidth and resolution. In this paper, a low-cost, high-resolution solution to generating speckle-free sharply focused laser lines is presented. The key to this technique relies on only removing the spatial coherence in one dimension using a 1-D cylindrical lens array as a beam homogenizer. This beam homogenizer is then wrapped around and rotated about a central axis in order to remove the temporal component of the laser’s coherence. Since the plane-wave-like behavior is maintained along one dimension, this beam can still be sharply focused to a line. However, the spatial coherence and temporal coherence are reduced to the point that speckle is minimally visible.

Keywords: Laser scanning, Line scanner, 1D homogenizer, Speckle reduction, Rotating diffuser

1. INTRODUCTION

Sub-pixel interpolation is a technique widely used in laser-line scanning to bring the targeted z-height resolution below the size of an actual pixel [1, 2]. This technique relies on fitting a parabola (or higher-order curve) to the peak of the laser line to extract the position of the peak below the accuracy a single pixel. In industrial applications, this calculation must be very quick to minimize the time a scan requires. It is because of this desired speed that algorithms don’t rely on a fit through oversampled data [3], but instead interpolate with predefined equations where the number of data points exactly equals to the number of free parameters (see Fig. 1(b)). However, when analyzing several types of structured materials, the noise on the extracted curve can be large enough to sway the calculated peak as a speckle can become a large problem on some semi-rough surfaces[4].

![Figure 1](image-url)

Figure 1. Cross section taken from (a) a line scan of a reference probe and (b) the use of subpixel interpolation to enhance the available resolution to below that of a single pixel. The ‘x’ is the interpolated peak of the curve.

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Speckle is well known to be a product of both the spatial coherence of an illuminating wave and the surface roughness of the object it is illuminating. In many scanning applications, the surface roughness of the object to be scanned is a fixed parameter leaving only manipulation of the illuminating wavefront as the best means to reduce speckle and increase the accuracy of the laser scan. Unfortunately, reducing the spatial coherence of the laser has the effect that the laser can no longer be focused to a tightly defined spot. These standard speckle reduction techniques would therefore reduce the spatial resolution of any line scanner which employs such methods. For line-scanning applications however, the light must only be focused tightly in one dimension leaving an extra dimension available to reduce speckle through wavefront manipulation.

The routine used to solve for sub-pixel interpolation is given by the following steps:

1) Find the pixel with the maximum intensity
2) Use the following equation (Eq. 1) based on a parabolic equation to determine the sub-pixel position of the peak intensity

\[
\Delta x_p = \frac{1}{2} \frac{y_1-y_3}{y_1+y_3-2y_2}
\]

where \( \Delta x_p \) is the distance from the maximum in pixels, \( y_1 \) and \( y_3 \) are the intensity of the pixel from the left/right of the maximum intensity pixel and \( y_2 \) is the maximum intensity.

1.1 1-D Beam Homogenizers

Two-dimensional speckle reducing beam homogenizers suffer from the problem that they reduce the focusability of an incident laser and therefore hinder the attainable focus resolutions. Thankfully, in situations where a laser-line is required, one can take advantage of a system that reduces the spatial coherence in only one dimension. The principle is the same as 2-D but leaves a planewave-like solution in one direction while destroying the spatial coherence in the other. Figure 2(a) gives the schematic diagram of this process using a widely available 1-D lenticular array. In one dimension, the lenticular array converts the plane wave into a series of cylindrically expanding wave fronts thus reducing the spatial coherence of the wavefront. This element alone serves to partially reduce the speckle seen in the visible line but the temporal coherence also plays a role [5]. This is the first step to reducing the speckle of a laser-line scanning system while maintaining the minimum focus size for higher spatial resolution.

![Figure 2](image.png)

Figure 2. (a) Schematic of a 1-D rotating beam homogenizer used in this paper. The lenticular array extends all the way around the rotating disk. (b) Raytracing principle behind a 1-D diffusor.
Figure 2(a) demonstrates how the rotation of the diffuser eliminates the integrated temporal coherence of the laser beam. Some systems do this by strongly modulating a large mode area VCSEL which time averages the laser coherence in conjunction with a 1-D beam homogenizer. The system produce here relies on a time-varying wavefront deformation and a time-integrated varying speckle pattern over the course of the exposure of the CCD.

2. RESULTS

2.1 Initial measurements

The lenticular array used in these experiments was Edmund Optics part number 43-029. It is a molded optic made from acrylic with a pitch of 142 cylindrical lenses per inch each with an effective focal length of 0.254 mm. A 20 mW 405 nm laser diode was focused into a single mode fiber (Thorlabs S405-XP) to both clean up the beam profile and deliver the light from a remote location to the desired position in the line generation system. The light was then collimated by a 50 mm focal length spherical lens before entering into the system illustrated in Fig. 2(a). That line was then delivered 50 mm to the probe to be measured where it was refocused into a line. The camera used to acquire the profiles was an IDS UI-3580ML color camera with a 2560x1920 resolution and a pixel pitch of 2.2 microns. Both the red and blue color channels are partially stimulated by 405 nm light so a sum over these two channels was used for the line profile.

![Figure 3](image-url)

Figure 3. (blue line) Effects of speckle on a copper surface using only the 1-D homogenizer without rotating. (red line) Same as blue line only rotating the homogenizer.

Figure 3 clearly demonstrates the system’s ability to clean up speckle through the use of the time dependent 1-D diffusor. This effect however comes at the unfortunate cost of broadening the width of the line and thereby reducing the lateral resolution of the system. The cross sections in Fig. 3 were measured while keeping the probe stationary and the noisy narrower curve corresponds to measuring the cross section with no time-dependent averaging while the wider, smoother profile is taken with the lenses rotating.

While the initial results of the rotating time-averaged 1-D beam diffusor are promising, the ability to cleanly manufacture a stable structure still needs improving. It was realized during the experiments with the diffusor however, that a complicated structure for the time-averaging could be built into certain types of scanning measurements. In
particular, in measurements where the object remains in motion while capturing each line, it was found that the time-averaging over the integration time of the camera gave enough smoothing to result in line profiles such as those seen in Fig 1(a) and (b). As long as the object was moving fast enough when compared to the integration time of the camera, a stationary 1-D beam diffuser was enough to average out the remaining speckle seen to produce a clean intensity cross section. Figure 4(a) is the result of such a measurement. This picture is a 3D scan taken of a diamond turned reference surface (from Physikalisch-Technische Bundesanstalt, or PTB) with a surface roughness of 1 nm and a surface evenness of 50 nm. The techniques used here was a Thorlabs linear translation stage was set to scan at a constant speed while the camera was set to a given frame rate with the timestamp recorded. The camera and stage were configured to record a line every 5 μm along the scanning direction and the magnification of the imaging lens along the transverse direction was such that the pixel measurement size also corresponded to a 5.1 μm scale.

Figure 4. (a) 3-D scan of a 50 nm accurate reference probe. (b) Cross section of the same reference probe in (a) showing the precision of the method.

As can be seen in the above figure, the scan results provide a clear and sharp reconstruction of the system. Figure 4(b) is a cross section of the scan derived from one frame of the set of acquired line scans. Looking at the 50 μm depth profile between the position 2.5 and 3.0 mm in Fig. 4(b), the calculated RMS z precision for this system is 760 nm. This entire sample was scanned and analyzed with sub-pixel interpolation using MATLAB at a rate of 0.5 cm³/min.

2.2 Further Examples

Taking the developed system further, the next step is to attempt to scan a recognizable yet difficult object to test the limits of the system. The surface relief profile of a stamped €0.01 coin provides a challenge because the maximum surface profile height is 40 μm and the edges of the profile present a particularly difficult secondary laser line reflection which is very efficiently directed at the camera and causes false signals. These problems can be noticeably observed in Fig. 5(a) and (b) in the inner curve of the “C” and the upper right corner of the “1”. In this scan, the transverse magnification of the image was change in order to record the entire coin in a single pass. Here, the pixel size represents 8.2 μm. And all other parameters remained the same as in those used to measure the profile in Fig. 4.
These edge errors due to secondary reflections show up long before these features that cause the signal intersect the laser line. This will, in the future iterations of this scanner, make it possible to track these errors since the distance between two measurements based on how far the scanner has moved between two frames.

### 3. CONCLUSIONS

A hardware adaption to the laser standard line scanning system which minimizes errors due to speckle has been presented in this publication. The system utilizes the well-known 1-D beam homogenizer based on a low cost, 1D lenticular array which aids in removing the specular coherence from the scattered laser line. The homogenizer was then placed on a rotating mount to additionally time average the remaining visible speckle pattern over the integration time of the camera measuring the profile. However, by rotating the array, errors in the wavefront due to distortion caused a time-averaged increase in the focused line width. It was found however, that simply moving the sample during scanning while using a static 1-D lenticular array sufficiently reduced the speckle pattern so that a 3-point sub-pixel interpolation worked nicely. The enhancement of scans can be seen clearly, improving the measured line profile to a precision that is at the sub-micron level. Several hard to scan objects were analyzed and the system was shown to function both fast and accurately.
REFERENCES