Projection of speckle patterns for 3D sensing

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Abstract. In this communication we present the use of projected speckle patterns coming from a phase random mask for sensing depths and thicknesses. The sensing is based on the change of the speckle pattern with propagation and the lack of correlation between speckle patterns recorded at different depths or lateral locations. The principle is used for mapping thickness of transparent media, for depth ranging and for 3D mapping of diffuse objects.

1. Introduction

Along the years many methods have been proposed for 3D sensing, mapping and ranging [1]. One of the most extended principles is triangulation, either using conventional illumination [2,3,4] or coherent illumination [5,6]. A main drawback of triangulation is the shadowing that inhibit the mapping of steep surfaces. Other among the multiple optical 3D mapping methods are the coherence radar [7], the speckle pattern sampling [8] and holography. Holography can also be used for 3D mapping (or rather contouring) by the use of multiple wavelengths, multiple sources [9] or object displacement between two records [10].

Most coherent methods are influenced by the speckle patterns that happen when coherent light is reflected or transmitted from a rough surface [11, 12, 13]. They are the result of interference among light scattered from elementary microscopic element of the rough surface. Speckle techniques such as electronic speckle-pattern interferometry (ESPI) or speckle photography have been widely used for displacement measuring and vibration analysis [14,15,16,17,18]. This procedure produces correlation fringes that correspond to the object’s local surface displacements between two subsequent exposures, with or without an additional reference beam. Note that speckle photography or interferometry direct techniques can measure the distortion of an object, but not its actual 3D shape.

In this contribution we focus on using the decorrelation between different speckle patterns. The method is based on the study of the speckle patterns projected on a certain object. We propose to use a diffuse object, such as a ground glass, to project a speckle pattern onto the object. Inherent changes of the speckle pattern as it propagates will uniquely characterize each location in the working volume. In contrast with other methods, the projected speckle pattern is sensed and analyzed, and not the speckle pattern produced by the object itself.

In this paper we apply those speckle pattern changes to three different application 3D mapping for both transmissive and diffusively reflecting objects and range estimation. We map a 3D object or its
range observing the differences and similarities by the speckled patterns when an object is illuminated using light coming from a diffuser. The correlation between initial and final patterns decreases with the object displacement, so if the displacement is significant the speckle patterns are statistically uncorrelated. This approach does not depend on the distance/relative angle between the camera and the pattern projector and thus it affected by shadowing problems. Moreover the system is robust and reliable, as the only interferometric process is concentrated just on the speckle pattern generation and it does not depend on the object accurate positioning.

2. Projection of speckle patterns

The derivation is based on fully temporally coherent radiation. This condition can be easily attained if the laser used has a coherence length longer than the maximum path length difference in the setup, situation that occurs in the later analyzed setups. A ground glass object, \( g(x,y) \) (Plane G) normal to the optical axis [see figure 1] is trans-illuminated by a monochromatic parallel beam of laser light of wavelength \( \lambda \). Speckle patterns are recorded at plane C, parallel to the object plane. In the plane C, at a distance \( z \) from G, the amplitude distribution obtained by Fresnel diffraction equation is proportional to [19]:

\[
U(\xi,\eta) = \int \int g(x,y) \exp \left( j \frac{\pi}{\lambda z} \left[ (\xi - x)^2 + (\eta - y)^2 \right] \right) dx \, dy
\]  

(1)

In order to check the change due to propagation, assume that the diffuser is axially translated a distance \( \Delta z \) (see figure 1). The irradiance at C is given by taking intensity on Eq. (1) replacing \( z \) by \( z - z_0 \) as [19]

\[
I(\xi,\eta) = \int \int g(x,y) \exp \left( j \frac{\pi}{\lambda z} \left[ x^2 + y^2 \right] \right) \exp \left( j \frac{\pi \Delta z}{\lambda z} \left[ x^2 + y^2 \right] \right)
\times \exp \left( -j \frac{2\pi}{\lambda z} \left[ \xi \left( 1 + \frac{\Delta z}{z} \right) x + \eta \left( 1 + \frac{\Delta z}{z} \right) y \right] \right) dx \, dy
\]  

(2)

Interpretation of Eq. (2) shows that axial translation of \( g \) has two main effects [19]. One is a radial shift of the speckles linked to the magnification due to geometrical projection from the diffuser screen center to the recording plane. The other effect is a decorrelation of the corresponding speckles due to the quadratic exponential term.

Figure 1. Projection of speckle pattern from a ground glass at distance \( z \).

The first order statistic of intensity shows that the intensity obeys an exponential law with mean (and standard deviation) equal to the mean intensity, in the case of fully developed speckle. The second order statistics play a fundamental role. The average transverse size (radius) of the speckle pattern is:

\[
S_r = 1.22 \frac{\Delta z}{\Phi}
\]  

(3)
Φ being the diameter of the diffuser. With respect to the longitudinal extent of the speckles, the problem reduces again to the calculation of the axial correlation function of the intensity [13, 20], between two points separated axially by Δz. In this case the half width of the speckle is shown to be:

\[ S_L = 8\lambda \left( \frac{z}{\Phi} \right)^2 \]  

(4)

A simplified picture of the speckle pattern in the volume can be visualized by a set of spots at random locations with transverse and longitudinal size given by the previous equations. Note that the transverse and longitudinal sizes increase linearly and quadratically with the axial distance, respectively. In fact, for z large compared with the transverse dimensions of the experiment, the speckles are elongated along lines radiating from the diffuser center. As a main conclusion, two speckle patterns taken at lateral or axial distances larger than the transverse or axial speckle sizes will be uncorrelated.

3. Experimental results for transmission thickness mapping

For 3D mapping of transparent objects, we project laser light on a small circle on a ground glass, with adjustable diameter by means of a iris diaphragm. That illumination creates a speckle pattern in the volume after it, its distribution depending on the distance from the ground glass. The speckle in a certain plane, at distance z from the ground glass, is imaged on the CCD camera. The diaphragm is adjusted until the size of the speckle on the CCD equals a few pixels, giving a distinct speckle pattern image. The insertion of a transparent plane parallel plate between the camera and the diffuser changes the plane that is imaged in the camera by a distance Δz that depends on the thickness and on the index of the plate. The speckles lying in the image plane suffer a decorrelation when the light path increases more than \( S_L \).

We first calibrate the system by mapping the speckles for the thicknesses of interest. Then after placing an object composed of patches of plane parallel plates of different thicknesses and imaging the generated speckles pattern one may estimate its 3D mapping. The calibration plates (and those used in the later experiment) are set perpendicular to the optical axis, to null the lateral displacement of the speckle pattern.

We constructed an object containing spatial regions with no glass, glass of 0.5 mm and glass of 1 mm width. Figure 2 shows the reconstruction results while the reconstruction is done by the absolute value of the subtraction between the captured patterns and the reference patterns (obtained in the calibration process). The dark zones indicate detection. The segmented areas show the regions of different thickness of the object.

![Figure 2. Results of segmentation for Thickness mapping.](image)

4. Experiments for range measurement

We use the axial variation of a projected speckle pattern to estimate the axial location of a large object. The experiment of range estimation was performed in reflective configuration in which the ground
glass (diffuser) was used to project the speckle pattern on top of a reflective diffuse object and the reflection was imaged on a CCD camera. The system is shown in figure 3. Light from a laser source passes through the diffuser. The speckle patterns coming from that diffuser are projected on the reflective object and then recorded by a CCD camera. The effective size of the diffuser is adjusted by means of the diaphragm until the image of the projected speckle size is larger than the camera pixel for correct recording.

For range finding the object was positioned 80 cm away from the CCD camera. The diffuser diameter is set to get an illumination F number of 40 approximately, which corresponds to an axial decorrelation length of 6.8 mm. In order to capture the decorrelated speckle patterns a calibration process was done. It consists of mapping the object by capturing images reflected from 11 planes separated 5 mm apart. For quantifying the speckle pattern variations we use conventional correlation (integral of the product). In a first step we record reference images of the speckle pattern of a diffuse object (a matte white painted plate) at a set of axial distances. We take the 11 reference images, each one separated 5 mm axially from the previous. This set of images is indeed a 3D map of the speckle pattern in the volume of interest. Then, we move again in the object in the same axial distance range and obtain the correlation of every image with all the reference set. Therefore we obtain a collection of 11×11 correlation values between the 11 patterns at different distances and the 11 reference images, covering a total axial range of 55 mm.

In figure 4 we display the range finding results, showing the correlations of each image with the calibration set. As one may see the maxima appear only at the diagonal (auto correlation) while the distribution outside of the diagonal is small (cross correlation). For further clarification figure 5 is actually a cross correlation matrix of 11 by 11 while the indexes (1 to 11) on the horizontal axes represents the plane number and the vertical axis represent the correlation value. The diagonal of the matrix is the correlation value of two images taken at the same distance. The neat intensity separation between the autocorrelation values and the crosscorrelation ones permit to identify the distance of the pattern by crosscorrelation the pattern at a given unknown distance with the prerecorded patterns.

Note that the process does not depend on the microstructure of the pattern, as the ranging is performed on the projected speckle pattern and not on the imaging one. The spectrum of the captured image with only imaging speckle (with uniform illumination of the object) is basically white because the the Nyquist frequency of the CCD is much smaller than the typical frequency of the pattern. The effect of the imaging speckle is at pixel level and just reduces the SNR in the projected pattern comparison. Because of this fact the object itself is not relevant, provided that it is a fine diffuse object. As a
confirmation of this fact, the region of the test plate used for the experiments was not the same in the calibration images that in the test image, having thus a different microstructure in the field of view.

5. Experimental results for reflective objects 3D mapping

In the previous section we have used the large area correlation for the depth determination. In this section we propose the use of local correlation to map the depths of small regions in a 3D object. We use a calibration procedure similar to the previous one, capturing the speckle pattern projected on a white painted plate at a set of axial positions that cover the working volume. In this case the correlation is not performed for the full image as in the range finding case, but we rather perform a correlation of local windows of the object with the same region of each of the calibration patterns to give the final three dimensional mapping. Note that in this case the projected speckle pattern is capture from the surface of completely different objects during the calibration (reference plane diffuse plate) and during the mapping (the object itself).

A basic parameter that we need for the procedure is the minimum size of the correlation window that will separate the autocorrelation value of the speckle pattern from the cross correlation between two windows with uncorrelated (by depth changes) speckles. We use one of the reference images obtained projecting the speckle pattern on a plane plate. We perform autocorrelations and crosscorrelations between windows chosen at random positions in the field. The mean and the variance of the correlations are obtained for 500 positions. The results show that autocorrelation can be separated from crosscorrelation for windows size exceeding 3.5 times the speckle size. In the following experiments we have used a running window size of 10 pixels.

In Figure 5 we show the results that were obtained for a three dimensional object, made up with toy building blocks. The object occupied a volume of 40x25x30 mm. As a main advantage over most 3D mapping methods, the proposed procedure has virtually no shadowing as the illumination and image recording are performed from the same location.

![Figure 5. Speckle image on a 3D sample (left) and the 3D mapping (right).](image)

6. Conclusions

In this paper we have presented the optical usage of speckles for transparent objects thickness mapping, 3D diffuse object mapping and range estimation. The key concept is to use a ground glass that produce a pattern that changes with the depth inherently by free space propagation. The projected pattern decorrelates when it is sampled at two different positions separated either axially or transversally. The computation of the correlation between the actual pattern as projected or transmitted by the object and a set of calibration images allows the determination of the 3D location and/or shape of the object. The concept has also been applied to 3D mapping by computing the correlation between
the object and the reference images on a running window of small size. Despite of the relatively small resolution, the system is robust and is almost independent on the characteristics of the object. A significant advantage of the method is the absence of shadowed area and high configurability. Experimental results present the verification of the proposed directions.

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