Reconstruction of 3D Target Images from Wavelength-Dependent Speckle Intensity

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An image-reconstruction technique is introduced for recovering the 3D image of an object that is flood-illuminated by a frequency-scanning laser. In this technique, the speckle intensity at the receiver is detected by a 2D array of direct-detection "light buckets." Stepping the laser in frequency produces a 3D array of speckle intensity values that carries information about the location and complex amplitude of the scattering cells located on the target's surface. If both the amplitude and phase of the speckle pattern were known, the 3D Fourier transform of the speckle's complex amplitude would provide the target's 3D image, where the magnitude of a given voxel represents the scattering strength of the corresponding point on the surface of the object. Because phase information is lost in the direct-detection process, however, the spatial autocorrelation function of the 3D image is obtained, rather than the 3D image [1]. References 1-5 describe related work.

A computational approach is described for reconstructing the 3D image from its autocorrelation. The ability to reconstruct images from the speckle intensity offers a number of important practical advantages over methods based on direct imaging with a lens. These advantages come, of course, at the expense of increased computational demands. One advantage of 3D speckle imaging is that it reduces hardware requirements, making it possible to obtain high lateral resolution without the need for a large and precise optical lens or mirror. As in direct imaging, the resolution is determined by the extent of the collecting area. For speckle imaging, however, the collector may consist of a floppy array of intensity detectors. Another important hardware-related advantage is that the coherence length of the laser need only be as large as twice the object's range extent. In contrast, for a coherent laser radar, the coherence length must be at least twice the distance to the target. Yet another advantage is that it is not necessary to have phase coherence between the different laser-frequency steps—greatly reducing the laser requirements, while at the same time allowing for extremely high range resolution. A further advantage is that speckle-based imaging is less sensitive to atmospheric turbulence than direct imaging, particularly if the turbulence is weighted more heavily towards the receiver. The presentation includes theoretical predictions and experimental confirmation of this reduced sensitivity. It also includes a set of measurements done through water with varying degrees of turbidity.

*The author performed this work for MIT Lincoln Laboratory through a research subcontract with Focused Innovation, Inc.

This work is sponsored by DARPA under AF Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

The reconstruction approach is motivated by the fact that the autocorrelation is the weighted sum of shifted copies of the 3D image, where the shifts are obtained by sequentially placing each individual scattering cell of the object at the origin of the autocorrelation space. The 3D image is produced by eliminating all but one copy. The key to doing this is the fact that the overlap between the autocorrelation and a shifted replica of the autocorrelation always contains a complete copy of the 3D image, provided that the shifted copy is produced by placing its center point on top of any support point of the original un-shifted autocorrelation function. It turns out that there is also an inverted copy of the object in this overlap due to the fact that the autocorrelation function is blind to direction. If successive shifts are chosen such that the center point of each shifted replica lies on the same copy of the 3D image, then all points in that particular 3D copy survive. Ordinarily, the second shift breaks the symmetry and favors either the copy or the inverted copy. A well-chosen first shift may eliminate about 90% of the data points. Further shifts eliminate additional points until finally a set of self-consistent points remains. If no errors were made in choosing the shifts, then it is guaranteed that none of the points on the object being recovered have been lost. It may occur, however, that there are extra points that are not eliminated by this process. The number of extra points is minimal, however, if the height function of the object is single valued, meaning that each x-y cell corresponds to only one z value. In this case, the autocorrelation function collapses to a single height value at the origin, and because this point is effectively dragged through and overlapped with each point of the 3D image during the reconstruction process, the reconstructed image will also be a single-valued function. The only place where extra points may occur is where holes are filled in for those x-y values of the object where there is no surface.

Because of the above observations, the reconstruction process is reduced to determining a sequence of shifts that lie on the object to be reconstructed. The decision process becomes easier as the process unfolds because each new shift point must have survived all prior shifts, and the number of surviving points is decreasing. In many cases, it is possible to see fragments of bright copies of the object in the autocorrelation function. In these cases, one may begin the process by choosing these bright points as the initial shifts. The presentation covers additional means for determining new shifts.

In order to aid visualization, the process is demonstrated on a 2D face profile, where one dimension represents range and the other cross range. Although there is no wavelength tuning in these measurements, they do produce results corresponding to a 3D measurement, minus one of the cross-range dimensions. Figure 1 is a digital photograph of a face profile that was constructed by cutting the profile out of a sheet of retro-reflective material, sticking the profile to a glass plate, and illuminating with a laser beam. Figure 2a shows the resulting measured autocorrelation function as obtained by Fourier transforming the speckle pattern and averaging over several realizations obtained by slightly rotating the plate. Figure 2b is the autocorrelation function obtained by digitally calculating the autocorrelation from the measured direct image. These two images are remarkably similar, and the method is demonstrated on the data represented by Figure 2b. Figure 3 is the image resulting from the recovery process. Note that there is some widening of the image in the z direction, which is to be expected because the autocorrelation function has some spread in z near its center point.

Finally, the presentation describes reconstruction results for simulated 3D data as well as a potential system architecture for acquiring and processing speckle data.

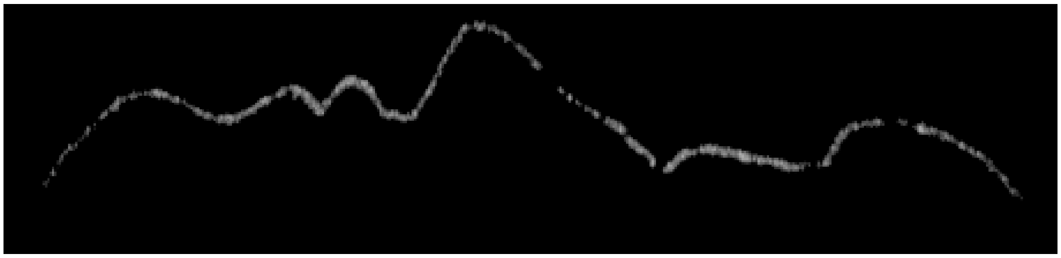

Figure 1. Digital image of face profile.

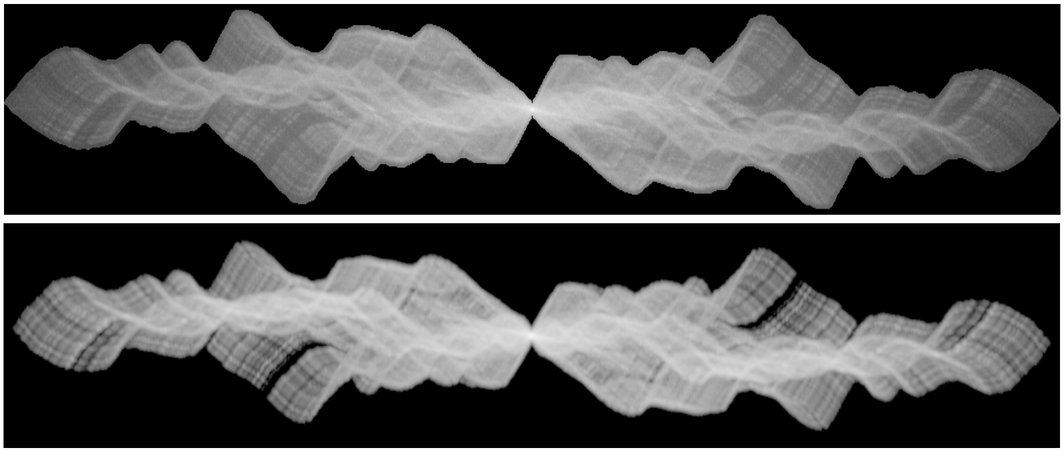

Figure 2. Autocorrelation of face profile obtained by (a) Fourier transforming speckle pattern, and (b) calculating autocorrelation of Figure 1 numerically.

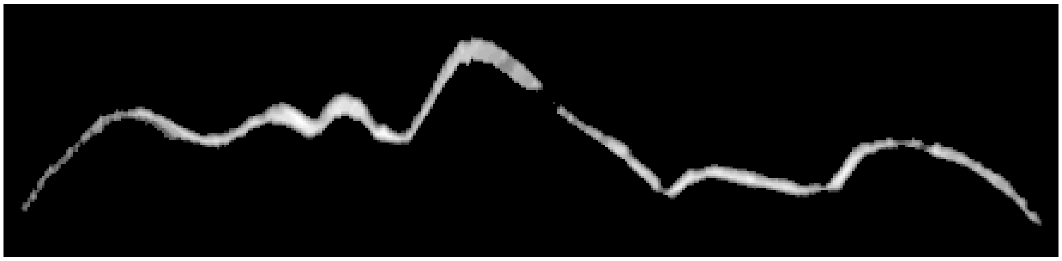

Figure 3. Image recovered from processing autocorrelation function.

References:

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