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Digital image correlation through a rigid borescope

Phillip L. Reu[1*]
[1]Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185

ABSTRACT

There occasionally occur situations in field measurements where direct optical access to the area of interest is not possible. In these cases the borescope is the standard method of imaging. Furthermore, if shape, displacement, or strain are desired in these hidden locations, it would be advantageous to be able to do digital image correlation (DIC) through the borescope. This paper will present the added complexities and errors associated with imaging through a borescope for DIC. Discussion of non-radial distortions and their effects on the measurements, along with a possible correction scheme will be discussed.

Keywords: digital image correlation, distortion correction

1. INTRODUCTION

Digital image correlation (DIC) has become a standard tool to measure 2D and 3D shape, motion and deformation. To conduct DIC in a hidden area a borescope may be a convenient method of imaging. There are two types of borescopes: fiber-optic scopes which use a lens and intervening fiber to relay the scene to the camera, or a rigid scope which uses a series of relay lenses to transfer the scene to a camera. Both types could be used for DIC; however the fiber-optic solution has severe image resolution limitations. Because of this, it was decided to use a rigid borescope system to attempt DIC in a hidden cavity. At the moment this limits the application to 2D DIC, however, arrangements could be imagined where 3D DIC could be conducted. Because of the complex optical path, distortions will be larger than a typical camera lens and likely not radial in nature. This paper discusses a proof-of-concept experiment conducted to determine the optical distortions and resulting errors in a DIC analysis. Furthermore non-radial distortion correction methods, which were originally developed for use in stereo-microscopes [1], will be used to minimize the distortions.

2. BORESCOPE DISTORTION TESTING

2.1. Experimental setup to determine lens distortions of a rigid borescope

A rigid borescope, model D8094K-101, was obtained from Lennox Instruments, a commercial manufacturer of both rigid and flexible borescopes. The borescope can be extended to various lengths using extension tubes. The optional prism objective was used on the end to create a viewing direction perpendicular to the borescope shaft. Dirt on the internal borescope lenses turned out to be problematic, as dirt spots look like a stationary speckle in the DIC and corrupt the results. After carefully cleaning the objectives, they were setup on an optical table looking at a small speckle pattern affixed to an *xy*-stage. The imaging section of the borescope is shown in Figure 1. The shorter borescope with only the eyepiece and imaging section was approximately 1 meter in length; the full borescope with two extensions was 2.8 meters in length.

The camera attachment for the rigid borescope was not appropriate for the Point Grey 5 Megapixel camera and caused severe vignetting on the 2/3-inch detector. The standard camera sold with the system is a much smaller and lower resolution detector and would not yield the desired spatial resolution for our application. To overcome the vignetting, a 75-mm lens was used to relay the image from the eyepiece to the camera (see Figure 1). With care and alignment, the vignetting was able to be minimized. A preliminary study showed that the effect of this additional lens was minimal on the distortions. The same 75-mm lens was used along with the same speckle pattern area to test the distortion removal algorithms and for comparison with the borescope results.

[*] plreu@sandia.gov

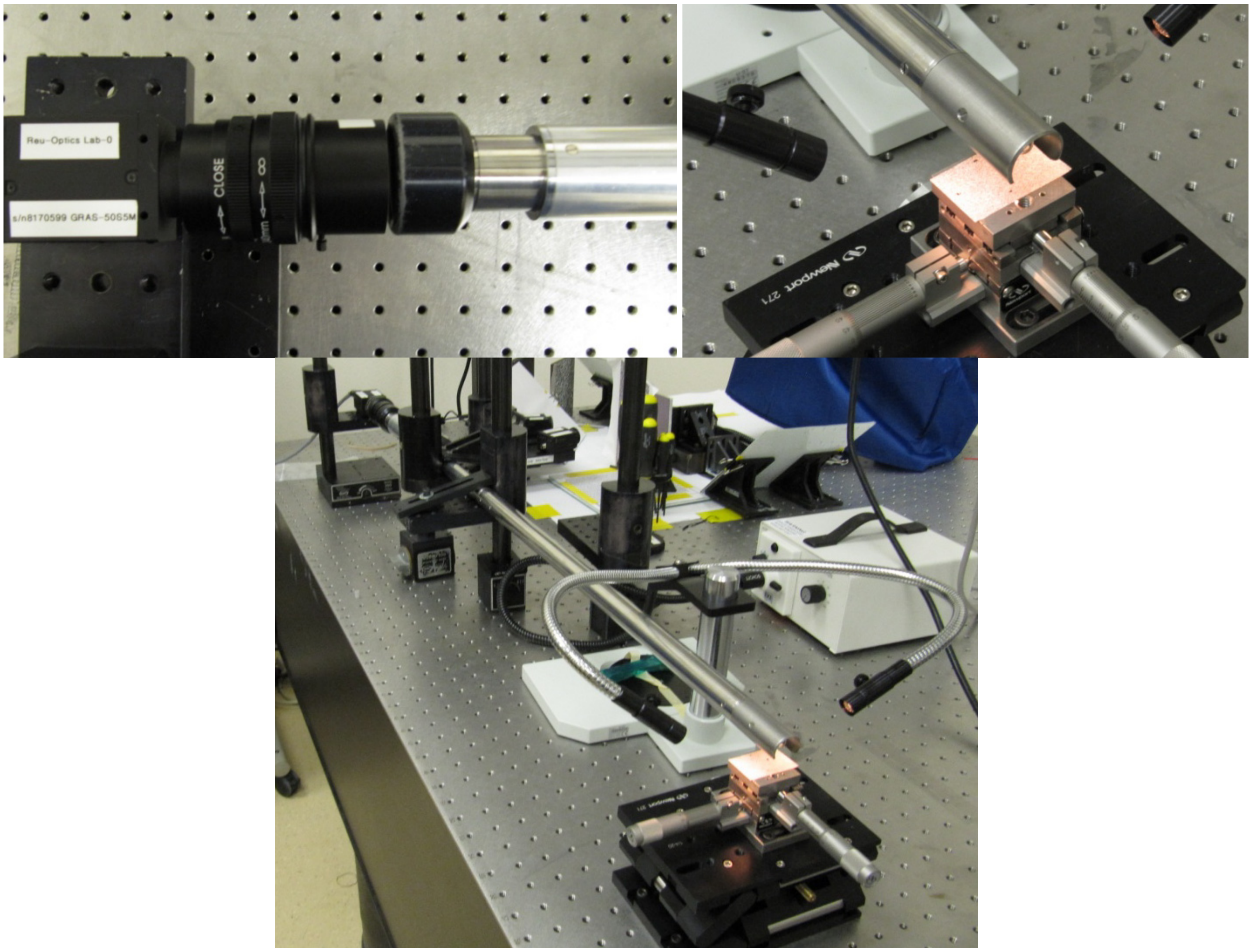

Figure 1. Borescope experimental setup. (Upper Left) Camera setup with relay lens. (Upper Right) Imaging end of borescope with lighting, speckle pattern and stages. (Bottom) Overall experimental setup.

2.2. Experimental procedure

After optimizing the focus and lighting, the speckle pattern was translated in an L-shaped pattern, with 6 images taken equally spaced in each direction. The step size used was 0.05 mm and was controlled with a manual micrometer stage. The total translation in the *x*- and *y*-direction was 0.3 mm (this corresponds to approximately 15.4 pixels in the sensor plane). Because this is a pure translation perpendicular to the lens, the results should be uniform noise overlaid on the translation. Any deviation from this is an indication of lens distortions. The translation results for the 75-mm lens and the rigid borescope before any correction are shown in Figure 3.

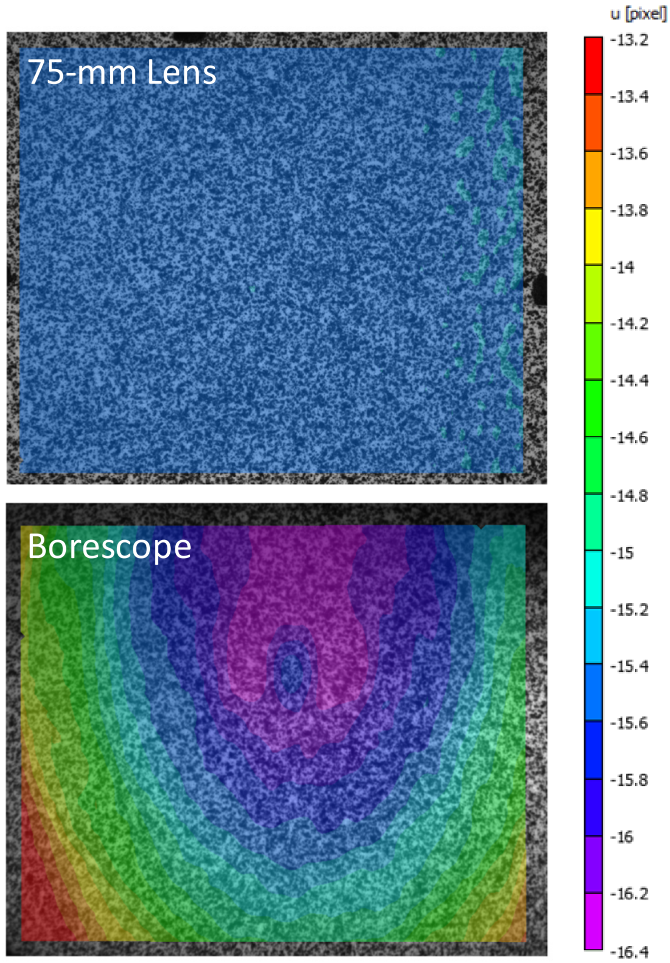

Figure 2. Optical distortions causing a “false” displacement result.

Figure 3 clearly shows that there is a large non-radial distortion caused by the borescope optics. In comparison the distortions are negligible with the traditional 75-mm optic. The question now to ask, is whether the borescope distortions can be removed?

3. DISTORTION CORRECTION RESULTS

3.1. Method of correction

To correct the distortions the same translated speckle pattern shown above was used. It is important that the pattern remain in plane and not be deformed during the translations. The built in distortion correction functionality of Vic2D was used for all results in this paper. The steps to correct the results include: 1. Running the correlation on the translated speckle pattern, 2. Fitting a spline function to the displacement data to map the optical distortion, 3. Correction of the data using the distortion map in subsequent correlations. The distortion correction also scales the data in millimeters if the correct translation amounts are entered into the software during the distortion correction. To calculate the results in pixels, the user may re-run the distortion correction algorithm entering the average displacement in pixels rather than in millimeters. All of the results in this paper are presented in pixel coordinates.

3.2. Correction results

After correcting the results as outlined above, the average displacement was subtracted from both the *x*- and *y*-translation results to show only the errors. The final distortion magnitude was calculated as the root sum of the squares of the *x* and *y* errors. Figure 4 shows the magnitude of the distortion at any given location in the field of view. Distortions as high as 0.3 pixels remain even after correction. Typically, for DIC to be useful, correlations on the order of 1/100ths of a pixel are desired. These distortions are 1 to 2 orders of magnitude higher than our desired displacement accuracy. Even more troubling are the errors in the strain results shown in Figure 5. Because the sample is unstrained in the translation, there should be no strain in the results.

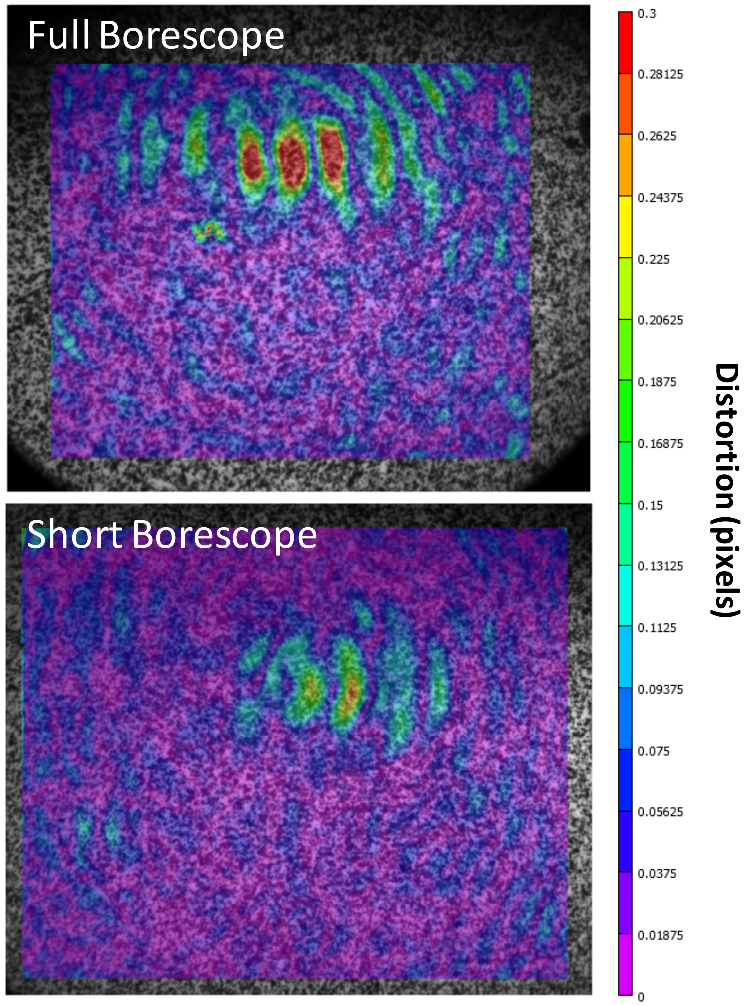

Figure 3. Corrected borescope distortions in pixels.

4. CONCLUSIONS

4.1. Summary of borescope distortion correction

While it is possible to greatly improve the distortion of the borescope imaging optics, with the current methodology, unacceptably large distortions still occur. This is especially true in the strain results, which give a measure of the slope of the distortion. The relationship between the distortions and the strain error is evident when the distortion results of Figure 4 are compared to the strain error results in Figure 5. The area of the largest errors corresponds to an area in the image that had particularly large distortions and was difficult to focus during the setup of the borescope. This problem was found to be in the final imaging portion of the borescope and was unable to be removed from the system. I suspect that either the imaging lens is miss-formed or misaligned. Because of the flaw in the borescope it is not possible to conclusively determine whether DIC through a borescope is possible. It should be noted that when the high distortion area is removed from the analysis, the strain results are a more acceptable 130 με. This leaves some hope that with a better (or maybe just different) borescope, much lower distortions could be obtained and DIC could be conducted through a borescope.

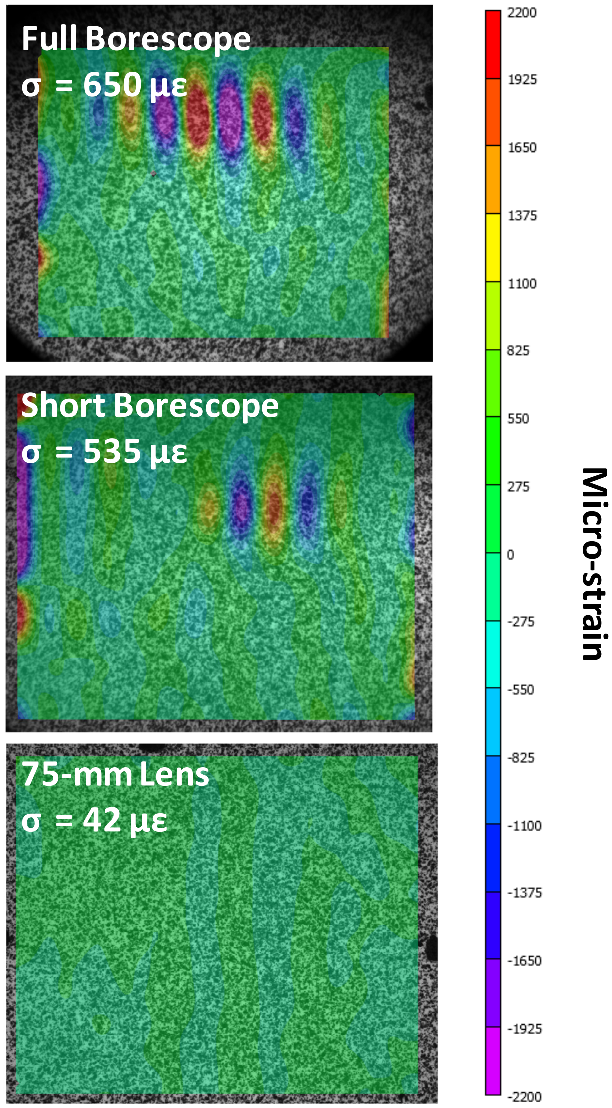

Figure 4. Corrected borescope Strain errors.

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5. REFERENCES

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