Calibrationless Aberration Correction through Active Wavefront Sampling (AWS) and Multi-Camera Imaging

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A typical lens used for optical diagnostics, whether for laser induced fluorescent (LIF), general flow visualization, or velocimetry, has distortions that result in displacement errors ranging from 10 to 100 pixels. While these errors are localized and thus do not necessarily have a strong effect on the magnitude of measured tracer displacement, they do strongly effect the imaged location and therefore, effect vector placement and direction in velocimetry techniques and thus can lead to significant errors when analyzing flows. Circular flow structures become elliptical, non-divergent flows become divergent, and irrotational flow becomes rotational.

The traditional way of calibrating cameras and correcting lens distortion is to image optical targets and use the known real-world position and relative positions of target features to find the parameters of a distortion model or to generate lookup tables (LUTs) which can be interpolated to find the undistorted pixel placement from distorted images. The accuracy at which cameras can be calibrated and distortion corrected is quite good using this approach but it is a very tedious and time consuming process. Furthermore, few fluid systems lend themselves to this approach for the simple reason that the volume of interest is generally within a sealed container and submerged. The problem is further complicated by flows which have optical diffraction characteristics that vary in time such as mixing and stratified flows. The desired solution would be a method of accurately calibrating cameras and removing lens distortion *in situ* using only observed features that naturally exist within an image. This paper presents such a method. By using multiple cameras (three or more) or by using active wavefront sampling (AWS), lens distortion and camera calibration can be accomplished without the need for a known optical target or known camera positions and orientations.

Multi-Camera Calibration and Lens Correction

Shashua (1995) established from homography a set of nine trilinear equations (four of which are independent) that can be used to uniquely define the mapping from three independent camera perspectives to the three-dimensional world. Based on these equations, three cameras can be used to establish the 3D position of features relative to one of the cameras without knowing *a priori* the relative position and orientation of the cameras to each other or knowing *a priori* the relative positions of imaged features. However, these equations are based on an ideal (pinhole) camera model. In real-world systems, cameras exhibit significant distortion and the accuracy which Shashua's equations uniquely define a mapping from the digital world to the real one, breaks down. However, these equations hold if distortion is removed. In the camera calibration and distortion correction method presented here, which is based closely on that proposed by Stein (1997) while at MIT, these equations are used as a way of estimating the ground truth from which camera distortion is corrected.

The algorithm presented for correcting lens distortion is based on the ability to identify a minimum of seven point correspondences in the projected space in each of the cameras. It is assumed there remains some residual error in determining these correspondences but that the same set of points are correctly identified to some relatively small inaccuracy. With seven points and three cameras, camera calibration parameters can be determined and radial distortion can be corrected to a scale factor. With additional points, higher order terms including tangential distortion can be corrected. The algorithm is based on finding the coefficients in the lens distortion model that minimizes the projection error between the positions determined by the lens distortion model and the positions identified by the 3D projection equations. With a minimal number of correspondence points, this procedure suffers from local minima requiring the use of advanced optimization techniques to insure that the true minimum error is determined. Larger numbers of correspondence points significantly reduce this effect. Once the coefficients of the lens distortion model are determined, the lens distortion equation can be used to correct the distortion of the entire imaged region from the perspective of the "third" camera identified by the 3D projection equations.

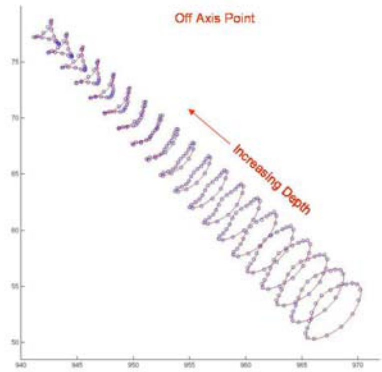

Fig. 1. Actual and model predicted paths of a single correspondence feature. The small circles represent actual image positions of the imaged feature at varying distances (depths) from an AWS camera focal position. The solid lines represent the calibration model's re-projected path.

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