MATLAB® based Image PreProcessing and Digital Image Correlation of Objects in Liquid

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Abstract

The venerable digital image correlation (DIC) technique relies on a series of digital images to obtain the incremental displacement and strain field on the surface of a specimen. In a standard DIC procedure, the image recording system and the object are kept in the same medium i.e. images are taken while the object is deforming in air. There is a growing need, however, to extend the use of DIC for objects undergoing deformation while being completely submerged under a homogenous solution. In soft-tissue engineering, for instance, tests are required to be carried out inside an organ culture system or in a fluid nutrient medium that mimics the native physiologic environment of a tissue. Regardless of the type of image recording system, such as waterproof camera, there is always image distortion caused by refraction. This refraction induced image distortion is nonlinear and non-uniform and that current camera calibration algorithms used in DIC systems don't have the capability to correct the refraction-induced image distortion and would give a highly erroneous result. This paper presents a Matlab based approach that uses the localized direct linear transformation technique to restore the refracted image. Once an image is restored it can be passed onto a DIC algorithm to obtain the desired kinematic variables following the usual correlation technique.

Keyword: Affine transformation, calibration-reconstruction, image distortion

Introduction

Measuring the deformation field of a liquid submerged body using digital image correlation (DIC), poses several unique obstacles to the investigator: these include the difficulty associated with placing the calibration grid in the liquids, insufficient illumination due to suspended particles, and image distortion by refraction. In standard DIC a rectangular calibration grid of known dimensions is positioned near the object to be deformed and a series of perspective images are acquired while changing the orientation of the grid. The system is then required to extract control points from the grid and match with known grid dimensions. Calibration in the context of three-dimensional stereovision is the process of determining the internal camera geometric and optical characteristics and/or the 3-D position and orientation of the camera frame relative to a certain world coordinate system [6]. A camera is considered calibrated if the principal distance, principal point offset and lens distortion parameters are known. The accuracy of the DIC system strongly depends on the accuracy of the camera calibration. Calibration of a DIC system while the calibration grid is submerged in a liquid is not always easy and attractive for several reasons: (a) the dispersion of light in liquid makes extraction of control points very difficult (b) in cloudy liquids, such as a soft tissue nutrient bath, the calibration algorithm will
not be able to accurately reproduce camera parameters due to lack of image clarity (c) often it is not desirable to immerse a calibration grid inside fluid filled container due to test related restrictions such as the case of a sterile and sealed organ bath (d) finally there is always image distortion due to refraction of light. These drawbacks often limit the use of this novel technique in many areas of experimental mechanics particularly soft tissue engineering. Current commercially available DIC systems are primarily designed for use in applications where the deformation is measured in air and as such there is no clear provisions that extend the use of DIC to submerged bodies. In a typical lab setting it is possible, however, to mitigate some of the above problems by manipulating experimental conditions and using image processing software to obtain an accurate deformation measurement of a submerged body. The method presented in this paper makes full use of MATLAB’s image processing tool box and Vic-3D® correlation algorithm to obtain a whole-filed deformation measurement on a submerged specimen.

**Refraction-Induced Image Distortion**

One of the most serious obstacles to accurately quantify the deformation of a submerged body using DIC is image distortion caused by refraction. Refraction occurs at the liquid-air interface owing to density differences. Camera calibration and reconstruction algorithms used in standard DIC technique are based on affine transformation. Affine transformation is a linear conformal mapping where a uniform translation, rotation, scaling, and shearing is applied to every point on the image. A single closed form mathematical expression is applied to an entire image to calculate intrinsic calibration parameters. Image distortion induced by light refraction, however, are nonlinear and nonuniform and cannot be accurately corrected by a single expression. The collinearity condition does not hold in liquid, because of the refraction-induced image distortion. The later depends on the degree of refraction and this inturn depends on the density of the medium involved and the angle of incident ray. For a homogenous optically isotropic material, Snell's law provides [1]:

\[
\sin \varphi' = \frac{k \delta / \sqrt{k^2 \delta^2 + \alpha^2}}{(1-k) \delta / \sqrt{(1-k)^2 \delta^2 + \beta^2}}
\]

where \( \varphi \) and \( \varphi' \) are the angle of incidence and angle of refraction. \( \alpha \) is the camera to interface distance \( \beta \) is the interface to object distance, \( \delta \) is the object to normal axis distance, \( k \) is the distance from the interface point to the normal axis normalize by \( \delta \) and \( c \) is the relative refractive index of the first medium to the second medium. the glass interface does merely shift the rays point of exit and has negligible effect on the angle of refraction. The relative refractive index is not a constant and varies with the ambient temperature and particle content in the liquid. For a given experimental setup, the constants \( \alpha, \beta, \delta \) and \( c \), the ratio \( k \) is obtained by solving[1]:

\[
(c^2 - 1)k^2(1-k)^2 \delta^2 + c^2(1-k)^2 \alpha^2 - k^2 \beta^2 = 0
\]

the computation of the ration \( k \) is important in developing a calibration algorithm as it is directly related to deformation of the image hence any calibration algorithm must consider this factor.
Direct linear transformation

The most widely used camera calibration algorithm, the DLT, is often used in underwater deformation analysis. The DLT method is based on the collinearity condition. The position of the calibration object in the object space and the position of the image point on the image plane are related by \([1,3]\). The coolinearity condition, however, does not hold in under liquid applications as shown in Fig.1.

The process of numerically finding the DLT coefficients of each camera is called calibration. Using a least square method, the DLT algorithm determines the parameters that minimize the calibration error \([3]\):

\[
u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1}
\]

\[
v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1}
\]

where \((x,y,z)\) are the object-space coordinates of the object point, \((u,v)\) are the image-plane coordinates of the image point, and \(L_1\) to \(L_{11}\) are the DLT parameters. The above equations can be combined together to form either a calibration form (Eq.5) or a reconstruction form Eq.6:

\[
\begin{bmatrix}
  x & y & z & 1 & 0 & 0 & 0 & 0 & -ux & -uy & -uz \\
  0 & 0 & 0 & 0 & x & y & z & 1 & -vx & -vy & -vz
\end{bmatrix}
\begin{bmatrix}
  L_1 \\
  \vdots \\
  L_{11}
\end{bmatrix}
= \begin{bmatrix}
  u \\
  v
\end{bmatrix}
\]

\[
\begin{bmatrix}
  L_1 - uL_9 & L_2 - uL_{10} & L_3 - uL_{11} \\
  L_5 - uL_9 & L_6 - uL_{10} & L_7 - uL_{11}
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}
= \begin{bmatrix}
  u - L_4 \\
  v - L_8
\end{bmatrix}
\]
\[
\varepsilon = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\varepsilon_{ui}^2 + \varepsilon_{vi}^2)}
\]  

(7)

where \( \varepsilon \) is the root mean square (RMS) calibration error, \( n \) is the number of control points, and \( \varepsilon_{ui} \) and \( \varepsilon_{vi} \) are the errors in the uv-coordinate:

\[
\varepsilon_{ui} = u_i = \frac{L_4x_i + L_2y_i + L_3z_i + L_4}{L_9x_i + L_{10}y_i + L_{11}z_i + 1}
\]  

(8)

\[
\varepsilon_{vi} = v_i = \frac{L_4x_i + L_2y_i + L_3z_i + L_8}{L_9x_i + L_{10}y_i + L_{11}z_i + 1}
\]  

(9)

Unfortunately, the DLT algorithm, albeit the most commonly used camera calibration algorithm, cannot correct the nonlinear errors caused by refraction[1,3,10]. Failure to correct the errors in the image coordinates caused by refraction results in an inaccurate quantification of the kinematic variables.

MATLAB Based Image Restoration

Matlab is a high-level technical language and interactive environment maintained by the MathWorks Inc. It has a plethora of subroutines and built in functions dedicated to perform complex image processing and manipulations and when combined with user developed subroutines its capability becomes limitless. Images are stored as two-dimensional arrays (matrices), in which each element of the matrix corresponds to a single pixel in the displayed image (spatial domain) that represents the intensity of the image at that point. For example, an image composed of 100 rows and 200 columns of different colored dots stored as a 100-by-200
array of positive integers. The value of each element of the array depends on the digital camera and image acquisition electronics [6]. Images can be added (imadd) or divided (imdivide), or image subtracted (imsubtract) to detect differences between two or more images of the same scene or to enhance or suppress certain features. In Matlab, images can also be stored as an array of complex exponential to manipulate frequency domain attributes. Frequency domain transform is useful for a wide range of applications, including convolution, enhancement, feature detection, and image compression [9].

Spatial Transformation and Image Restoration

A spatial transformation modifies the spatial relationship between pixels in an image, mapping pixel locations in a given image to new locations in an output image. Recall that an image of a submerged body exhibits refraction induced nonlinear distortion owing to the noncollinearity of a point in an object space to a point in an image plane. The refraction distortion can be viewed as a shift in spatial coordinates of each pixel in the image from its original location. This shift is nonuniform by nature and the refracted image is larger than its un-refracted counterpart with the degree of nonlinearity being proportional with the angle of refraction[1]. The approach adopted here involves forcing the distorted image of the submerged calibration grid to fit its actual shape and size and in the process obtain the spatial transformation matrix.

Experimental procedure

Perspective images of a 10x13 calibration grid were used to calibrate the DIC system that has two 1.3MPixel CCD cameras (QIMAGING® RETIGA 1300) and 35mm lens. The calibration images were acquired while the grid is inside the empty tissue bath which has a clear viewing window made of a plexiglass Fig.5. The cameras are calibrated by required the system to extract the control points and ensuring that the error is within the acceptable margin often a default value specified by the specific DIC system. As a next step images are acquire by placing the calibration grid at the same spatial location but this time with the bath filled with sodium chloride irrigation solution which was later used for testing membranous collagen matrix. When acquiring the submerged images the cameras are not refocused to insure that calibration is not disturbed.

![Figure 3](image_url) Calibration grid in air (left), in liquid (right)
Figure 4 Background intensity distribution of the two images

Figure 4 shows the reference image, the image in air, and the submerged image of the calibration grid. The submerged image has shifted to the left and is larger in size than its true counterpart. The dimensions between dots are non-uniform and will not conform to the specification of the calibration frame. If this same image is passed to the correlation algorithm the result will be highly erroneous. The submerged image is also prone to blurring, or degradation, due to scattered light distortion and it requires image enhanced. Histograms often provide information required to choose an appropriate enhancement operation Fig.8.

If we fit the refracted image-plane coordinates to the object-plane coordinates, a mismatch error occurs as shown in Fig.6. The O's shown in the figure are the real coordinates of the control points while the ●'s are the coordinate of the distorted image. The control points at the edges generally show overestimation errors while the rest of them show a trend of underestimation of the distance from the center. The maximum calibration error occurs at the outer-most edge.
Discussion

As it is said earlier, the purpose is to restore the distorter image back to the shape and size it should be had it its image was acquired in air. Consider two images one refracted-distorted and the other reference and normal image. the two images are acquired without changing the camera position or lens settings (no refocusing) and that the calibration grid was at the same spatial coordinate location both cases. Since everything else has been kept constant, any variation between the two images should be the result of light refraction. the difference between the two images can be represented by the discrepancies in the spatial location of control points or pixels on the two images. The spatial relationship between the distorted image space and the true undistorted space can be approximated by defining a local weighted mean (LWM) transformation. LWM is the mean where there is some variation in the relative contribution of individual data values to the mean. Each data value \( X_i \) has a weight assigned to it \( w_i \),

![Figure 6 Mismatch errors due to refraction distortion, Actual images (left), viewing aid (right) • Refracted, ○ Reference](image)

![Figure 7 Histogram of the reference and underwater images](image)
The LWM is required to restore the distorted image space as the refraction distortion is non-uniform by nature with points at the corner of the grid experiencing more distortion.

\[
X_m = \frac{\sum w_i X_i}{\sum w_i}
\]  

(10)

The LWM transformation matrix is created in MATLAB using 12 control points on both images as shown in Fig.10. The transformation matrix will then be used to transform all images to correct the refraction distortion before the latter is passed to the correlation algorithm (VIC-3D). The steps involved are briefly sketched in Fig.9.

**Conclusion**

The digital image correlation (DIC) technique relies on a series of digital images to obtain the incremental strain field on the surface of a specimen. In a standard DIC procedure, the image recording system and the object are kept in air. There is a growing interest, however, to extend the use of the DIC technique for submerged bodies. In biomedical engineering, for instance, tests are required to be carried out in an organ culture system or in a nutrient medium that mimics the native physiological environment of a soft-tissue. Regardless of the type of image recording system, such as waterproof camera, there is always image distortion caused by refraction. Refraction occurs at the liquid-air interface owing to density differences. This refraction induced image distortion is nonlinear and non-uniform and that current camera calibration algorithms used in DIC systems don’t have the capability to correct the refraction-induced image distortion and give erroneous result. This paper presented a Matlab based approach that uses the localized direct linear transformation technique to restore the refracted image. Restoration is achieved by comparing a distorted image of a calibration grid with its undistorted counterpart and in the process obtaining a spatial transformation matrix. The latter is then used to restore distorted images of the test specimen. Once images are restored they are passed onto a DIC algorithm to obtain the full-field strain following the usual correlation technique.
Reference Image of
the calibration grid  
Distorted Image of
the calibration grid  
Distorted Experimental images

Select Control points
\{cpselect\}  
Fine tune control points using \{cpcorr\}  
Pass points to \{cp2tform\} to create spatial transformation Structure, \{tform\}  
Perform the spatial transformation passing \{imtransform\} the TFORM and the distorted  
Align the distorted image with the reference image and  
Estimate the alignment error  
MATLAB®  

Read images into Matlab workspace  
Perform spatial transformation using TFORM  
Obtain restored experimental images  
Input images into DIC correlation algorithm  
Full-filed strain , strain rate…  
VIC-3D®

Figure 8 Flow diagram, Images are first corrected for refraction using MATLAB® and digital image correlation is performed by VIC-3D®
Matched pair of control points

Figure 9 Control point selection, Distorted image (left), reference image (right). A minimum of twelve matching pair of points are required to restore the refracted image using local weighted mean (LWM) transform

Figure 10 Refracted and reference image overlay before transformation (left), and after transformation (right). Arrow indicates the boundary of the refraction-space once it has moved to overlap with the true image space
References