Image Registration for Pressure Sensitive Paint based on Improved Feature Detection Criteria

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***Abstract**: Image registration of a Pressure Sensitive Paint (PSP) is an important part of studying a model in a wind tunnel. To increase the accuracy of registration process, the image pairs of both wind-off and wind-on states have to be aligned precisely to study the effects of wind pressure on the model effectively. The features must be extracted from the images, then to match these features, and finally applying the required transformation to complete the registration process. Harris corner detection algorithm used to extract the corners from both wind-off and wind-on image, edges detected by Canny-detection algorithm, and Hough-transform applied to detect lines of the images, matching each neighborhood pair of corners to get the most matched corners. The experiments done on many sets of images showed the effectiveness of this detection algorithm and gave the possibility to modify and enhance the process.*

Keywords: Pressure sensitive paint, Harris-corner detection, Hough-transform, image registration, wind tunnel

1. Introduction

The image registration has been carried out a lot of research work, a variety of methods or techniques were put forward. Registration based on corner detection as feature extracted has the merits of the rotation invariant and almost immunity to illumination conditions [1]. Image registration is a crucial part in studying the wind pressure effects using the pressure sensitive paint (PSP) technology.

The pressure sensitive paint (PSP) is relatively a new measurement technique for global surface pressure measurements in aerodynamic systems. The fundamental operating principle of PSP is oxygen quenching of luminescence from the paint. Light intensity emitted by the paint is measured by a photodetector [2]. This technique is used in the wind tunnel applications to get the required data for image registration of wind-off and wind-on images. One image is taken at a known “wind-off” reference pressure while the other is taken at the test condition” wind-on”, to factor out the effects different factors affecting the wing.

In order to well-recognize these effects like model deformation, nonuniform illumination, paint thickness, and wind pressure effects, the markers are used according to certain criteria as input tools which located on the model. The pressure data can be extracted only as a ratio between the “wind-off” and a “wind-on” image in case of exactly aligned images so as the pixel-by-pixel comparison of the registered images shows the wind pressure effects on the model through the studying of intensity changes on the model images.

As the wind-on/wind-off image pairs have been captured they required processing. The brightness (intensity) of the PSP coating is recorded by a camera as gray scale values. The ratio of the wind-off image intensity (I_0) which is in static case (no air flow) is made with wind-on image (I) under air pressure effect, so, the variation in the ratio-image intensity can be related to pressure change, as described by the Stern-Volmer equation[2]

$$\frac{I_0}{I} = A + B\frac{p}{p_0} \qquad (1)$$

Where p and p_0 are the wind-on and wind-off pressures, respectively, and A and B are coefficients specific to PSP chemistry.

The image rationing requires that the wind-off and wind-on images are exactly in the same position. But the studies showed that these two images did not still aligned correctly because of the model deformation and displacement due to wind pressure. This requires repositioning of the two images prior to measure ratios of equation (1)

2. System Arrangement

The model under test is fixed in the wind tunnel which is regularly illuminated by the illumination sources to enable the camera to catching up both wind-off and wind on images in exactly the same illumination conditions. Also, it is important to keep camera and illumination sources out of wind pressure effects to guarantee that the factors of equation (1) are only the factors of concern.

Artificial markers are fixed in the model to be good features can be relied on them in the next processing steps. The following figure shows the arrangement of model test [3]:

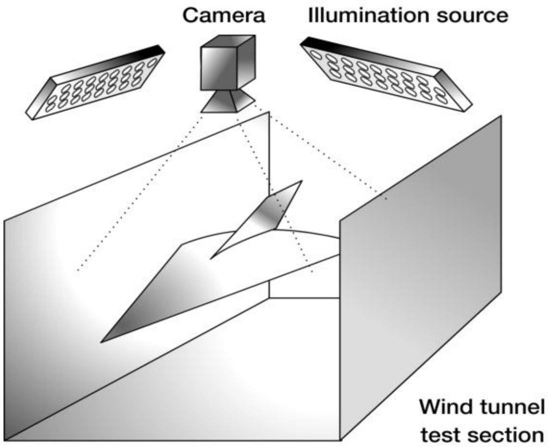


Fig. 1: Arrangement of model under test in the wind tunnel

A wind-off image is a reference image used later in the next steps of processing, while the wind-on image recorded under the wind pressure. Basic features like corners are extracted from this pair, matching of these corners is performed to observe the number of matched corners and then to apply further matching algorithm like cross-correlation matching algorithm. The outcome of this step is a number of matched points sufficient to be used in the next steps of transformation application and image registration. These steps are summarized in the following block diagram:

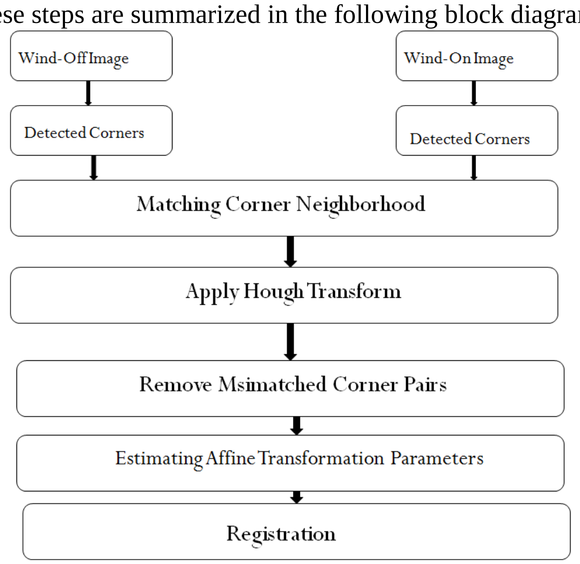


Fig. 2: Block diagram of the PSP image processing system

3. Harris-Corner Detection Algorithm

Harris corner detection algorithm is a kind of extraction operator based on signal point feature and only involves the first derivative of the image; its principle is to make the image window ω moved in any direction, its intensity variation in the shift u,v can be defined as :

$$E(u,v) = \sum_{x,y} w(x,y)\ [\, I(x+u,y+v) - I(x,y)\,]^2 \qquad (2)$$

Where w(x,y) is window function
I(x+u,y+v) is the shifted intensity
and I(x,y) is the intensity

For small sifts [u,v] we have a bilinear approximation:

$$E(u,v) \cong \sum w(x,y) \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$

(3)

Note that the values inside the matrix in equation (3) above are products of the components of the gradients I_x and I_y

3.1 Feature Detection and Corner Matching

As the Harris corner detection algorithm applied on a pair of wind-off and wind-on images with different quality sizes (thresholds) we get the following images:

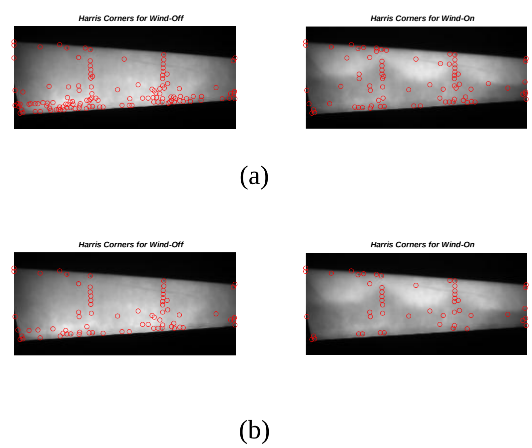


Fig. 3: Harris corner detection(Set I) on wind-off and wind-on images with (a) Smaller threshold (b) Higher threshold

As shown in fig.3, the number of detected corners could be controlled by adjusting the threshold factor of the Harris detection algorithm. A trade-off between the number of detected corners and the unmatched ones could be done to get a reasonable computation time.

To test the wind pressure effects on the PSP and the possible translation and rotation, we apply a motion test by computing the difference in the intensity level of corresponding pixels between these images.

The applied motion and intensity differentiation test on the set of wind-off and wind-on images of fig. 3-b shown in fig.4:

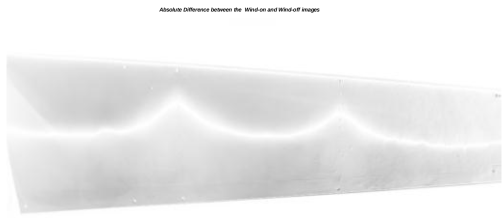
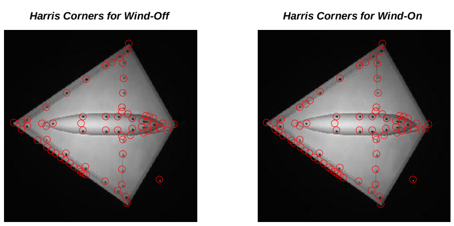


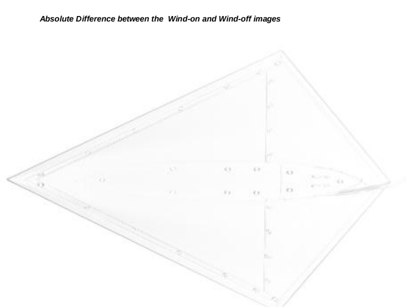
Fig. 4: Motion and intensity differentiation test on wind-off and wind-on images set(I)

It is obvious from fig.4 that there is an intensity difference between wind-on and wind-off images as well as the motion effects; the translation and/or rotation of the model resulted from the wind pressure.

Also, this test applied to other two sets of wind-of/wind-on images:

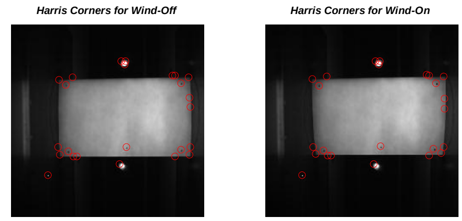


(a)

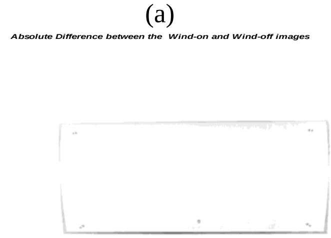


(b)

Fig. 5: Set (II) of wind-off and wind-on images (a) Harris corner detection (b) Motion and intensity difference test



(a)



(b)

Fig. 6: Set (III) of wind-off and wind-on images (a) of Harris corner detection (b) Motion and intensity difference test

3.2 Corner Matching

The cross-correlation coefficients calculated in order to perform the correspondence between the detected corners in wind-off/wind-on images. The cross-correlation coefficient is estimated by the following formula:

$$Corr(i,j) = \frac{cov(i,j)}{std(i) \times std(j)} \qquad (4)$$

Where i,j are any two corners in wind-off/wind-on images, respectively[4]. The corner point neighborhood is defined as the pixel region which takes i or j as the center and has a window size,

$$\omega_s = (2n+1) \; X \; (2n+1)$$

and then find the corner pair whose absolute value of the normalized cross-correlation is greater than a threshold

An appropriate number of matched corners for each set of wind-off/wind-on images are obtained. It is obvious from noting the above table that the number of detected corners and the matched corners is different depending on the test images. One of the test sets gave enough number of matched points by simple comparison of detected corners of wind-off/wind-on images, but in general, a point matching algorithm must be applied.

4. Hough transform and edge detection

The Hough transform is a popular robust statistical algorithm for extracting global features such as straight lines, circles, or ellipses from an image, which is widely used in image processing and machine vision. Given an NxN binary edge image, straight lines are defined in the equation:

$$\rho = x \cos \Theta + y \sin \Theta \qquad (5)$$

Where (x,y) is the measurement of position X-Y coordinates, Θ $(0 \leq \Theta \leq \pi)$ denotes the angle the normal line makes with x-axis, and ρ (-N ≤ ρ ≤ $\sqrt{2}$ N) is the normal distance from the original to the line [9]

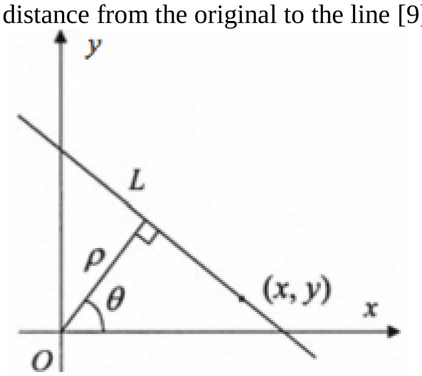
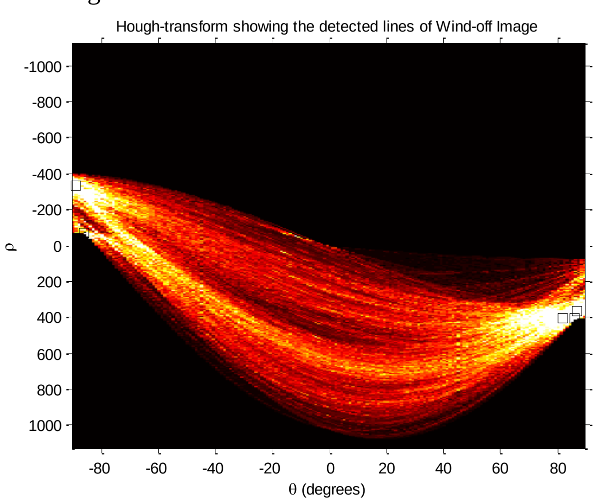
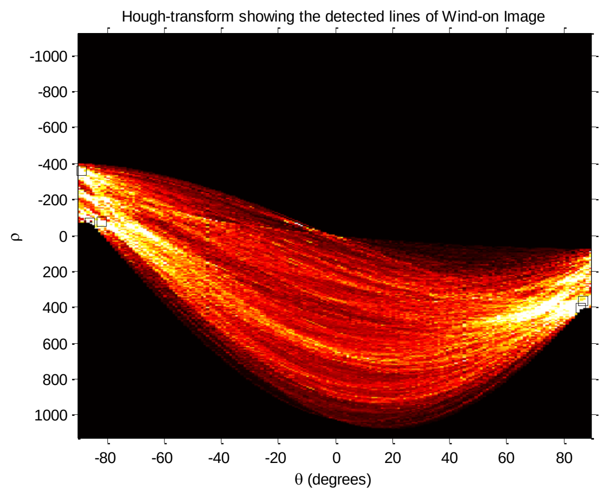


Fig. 7: Relationship between (x,y) and (ρ,Θ)

The Hough transform was applied to the pair of wind-on/wind-off image after the canny edge detector has been applied first. The detected lines by the Hough transform for these images shown below:



(a)



(b)

Fig. 8: Lines detected by Hough transform after applying Canny-edge detector for (a) Wind-Off image (b) Wind-On image

It is clear that the positions of the lines are changed either because of the displacement occurred due to the wind pressure or because of the effects of the wind pressure on PSP layer.

The lines detected by the Hough-transform as well as the corners detected by the Harris-corner detector are applied to the wind-on image as shown below:

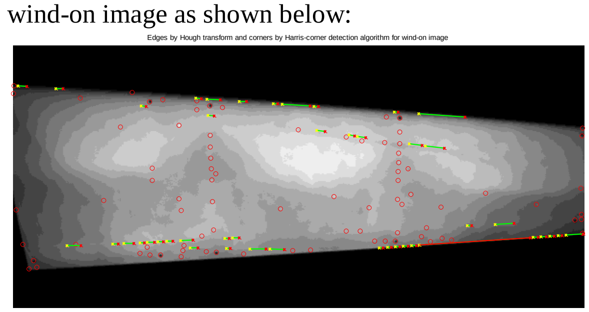


Fig. 9: Edges by Hough transform and corners by Harris-corner detection algorithm for wind-on image

These lines make sense about the more important points or real points and together with cross-correlation help to select the coordinates used in registration operation.

5. Affine Transformation Estimation parameters

After determining the registration points, it is required to fit the six best parameters of affine transformation. Assuming the selected control points sequence in Wind-off image is:

$$(x_1,y_1), (x_2,y_2), \ldots\ldots\ldots\ldots , (x_n,y_n)$$

The matrix of six parameters [4] of affine transformation P:

$$\begin{bmatrix} a_{00} \\ a_{01} \\ t_x \end{bmatrix} = P^{+}\left[x_1^{'}, x_2^{'}, \ldots, x_n^{'}\right]^T, \begin{bmatrix} a_{10} \\ a_{11} \\ t_y \end{bmatrix} = P^{+}\left[y_1^{'}, y_2^{'}, \ldots, y_n^{'}\right]^T$$

Where P^+ is the generalized inverse matrix of P.

This transformation applied to the image set (II) to perform the registration process, and we get the following registered image:

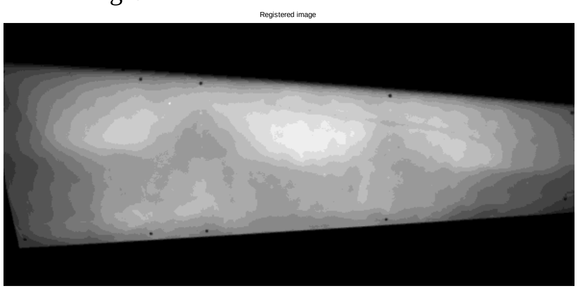


Fig. 10: Registered image of set (I1) wind-off/wind-on images

Also, a motion test and intensity difference applied to the registered image to notice the difference with motion test of unregistered image, this is depicted in the following figure:

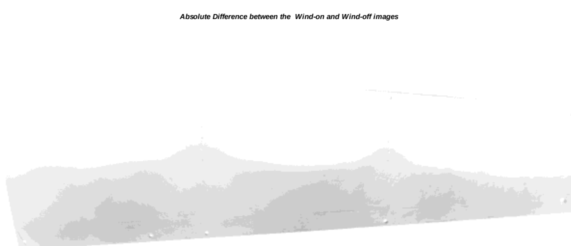


Fig. 11: Motion test and intensity difference for Registered set

Conclusions

- Corner detection helps to detect both natural features and artificial markers.
- There is a flexibility to change the number of detected features to accommodate specific applications.
- Problems of Harris-Corner detection algorithm:
  - The ability to distinguish the corner from the peak and the dip.
  - The robustness to noise.
- The Hough-transform with the canny-edge detection was applied to get better performance in specifying the more related corners used in final alignment.
- It is possible to perform a 3-D image resection because of the expected pending in the wind.

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