Correcting drift and spatial distortion in scanning electron microscope images for effective Digital Image Correlation

A thesis submitted in fulfilment of the requirements

for the degree of ***Master of Technology***

by

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Certificate

It is certified that the work contained in this thesis entitled **Correcting drift and spatial distortion in scanning electron microscope images for effective Digital Image Correlation** by **Atul Kumar Gautam** has been carried out under my supervision and that it has not been submitted elsewhere for a degree.

August 2022

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Abstract

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Digital image correlation is a popular and adaptable technique used to obtain the full-field displacement fields on a sample's surface. This technique has been used in-situ on specimen which are deforming inside a Scanning Electron Microscope(SEM). However, numerous scanning artifacts are developed during the scanning process due to the electron beam's distortion or relative motion between the specimen's surface and the electron beam emerging from the SEM's electron gun. These aberrations can potentially cause inaccurate displacement measurements when using digital image correlation . The two most critical imaging artifacts are drift and spatial distortions. This thesis uses a calibration technique to estimate the extent of these distortions and remove them to perform an effective DIC.

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Abbreviations

DIC	**D**igital **I**mage **C**orrelation
SEM	**S**canning **E**lectron **M**icroscope

Dedicated to my parents

Chapter 1

Introduction

Experiments with small-scale deformation are a distinctive and essential aspect of material science. On the surface of small samples, it is often possible to detect the atomic distortion technique that occur throughout the deformation and failure of specimen [1]. This small-scale deformation on the surface of tiny workpiece can be obtained using the Digital Image Correlation method. One can use the non-contact optical technology known as digital image correlation (DIC) to quantify displacements throughout an entire field. Conventional strain measurement devices have limitations, such as the inability to construct a full-field strain map, however DIC is a technique used to build a full-field strain map. To carry out the DIC method, we first take two separate digital photos, which we will refer to as the reference and current images of the specimen surface, respectively. To acquire the pictures of the specimen surface, we used a scanning electron microscope device. Creating pictures of a material using a scanning electron microscope involves passing a focused ray of electrons across the material's surface in a scanning motion. It uses a raster scan pattern as its basis. The interaction of the electrons with the atoms in the sample causes various signals production, each containing information regarding the surface topography and composition of the model. When the beam's orientation and observed signal intensity are combined, an image is formed.

The scanning electron microscope, often known as SEM, is a piece of the standard equipment used in almost all nanotechnology labs, both in corporations and academic institutions. SEM is an effective general-use instrument due to its ability to scan bulk samples with only a minimal amount of sample preparation required and its images, which are easy to understand. Several problems are associated with utilizing SEM pictures that affect the DIC procedure [6].

These defects, which are referred to as SEM imaging artifacts, are as follows:

1 - Shifting of scan line

2 - Noise in the image

2 - Drift Distortion

3 - Spatial Distortion

Shifting of scan lines occurs due to alignment errors made by the concentrated electron beam across the object's surface during scanning process [7].

SEM enables the capturing of images at various scan speeds. Image noise, which occurs when we take photos more quickly, presents another issue. Several filters are applied to the images to remove the noise, depending on the type of noise produced[4].

A time-varying artifact that occurs throughout the imaging process is called drift distortion [10]. The primary cause of the drift distortion is an unintended relative motion between the sample's surface and the electron ray that emanates from the SEM's electron cannon during the imaging process. It can also happen for other reasons, like when parts of the SEM's electron column and the sample get hot[9], when the specimen gets charged, or when the magnetic field interferes[5]. Drift distortion is more pronounced in images taken at a high scan speed.

Spatial distortion is the most critical spatially varying artifact. It doesn't have any effect over time. The main factor causing spatial distortion is the slightly intermittent electromagnetic field produced by the SEM equipment. Spatial distortion is more pronounced in lower-magnification images[8].

Due to the combined effect of spatial and drift distortion, the DIC results can be drastically altered, and the resulting images will be more deformed than they would typically be. It is necessary to use a calibration technique in which images are collected in pairs and rigid body motion is applied in between each pair because distortion rely on both space and time[11]. In order to improve the effectiveness of the DIC results, we can quantify the distortion during the calibration phase and eliminate it from the images.
Our main objective is to eliminate spatial distortion and drift from scanning electron microscope pictures to acquire precise small-scale deformation with the help of digital image correlation. This thesis describes a general implementation strategy for the distortion calibration stage for measuring drift distortion and spatially varying distortion.

Chapter 2

Scanning Electron Microscope

2.1 Working principle of SEM

A scanning electron microscope operates on the idea of transmitting a concentrated beam of electrons across the sample's surface. There are three main divisions for the SEM instrument as shown in fig.2.1:

1 - The creation of electron beams and their travel through various lenses and coils take place in the first section.

2 - The sample and specimen stage are located in a chamber in the second segment.

3 - The third section, which controls the process with the aid of an electrical device (e.g., a computer)

The term "electron column" refers to the first section. An electron cannon is found in the electron column. This electron pistol is connected to a high-voltage external power source to produce electrons at various intensities and rates depending on the specimen. Two condenser lenses are provided in the electron column, which are utilised to concentrate the electron rays through a narrow aperture. There is an objective lens at the bottom of the electron column. This lens's purpose is to build an electron probe. When the electron beam collides with the specimen's surface, it scatters. The detector gathers these dispersed electrons in the SEM, and utilize it to create an image of the sample's surface. In order to prevent the emission of scattered electrons, an electron cannon operates in a vacuum. The diameter of the objective lenses contains two scanning coils.

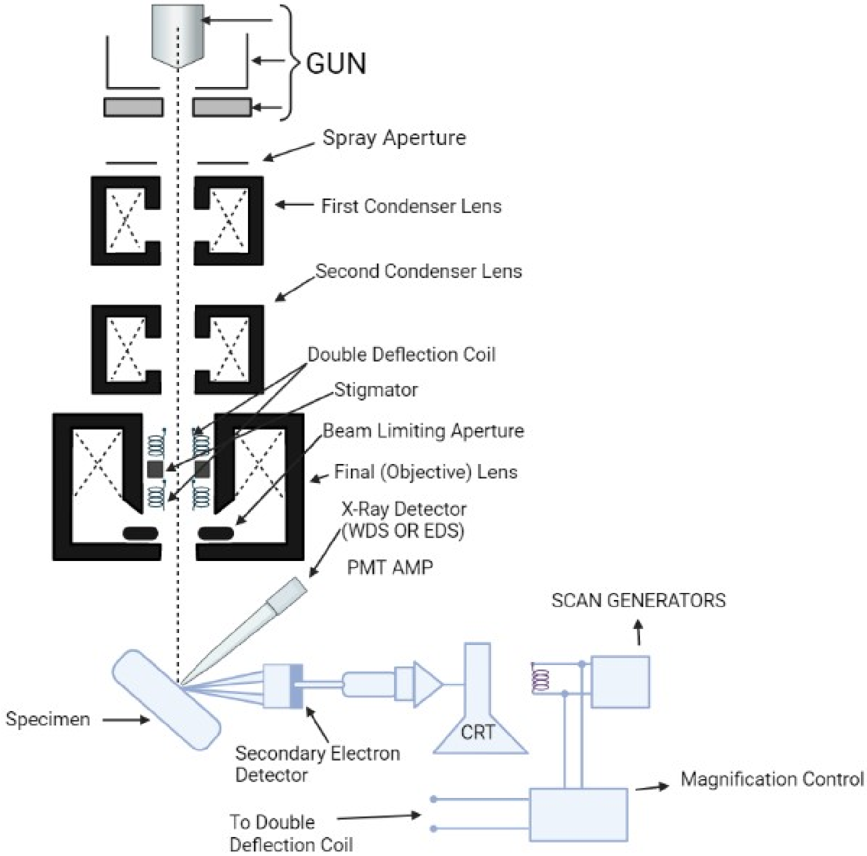


FIGURE 2.1: Schematic representation of a scanning electron microscope

These scanning coils assist in the point-by-point scanning of the sample's surface with the help of an electron probe, starting from left to right. The electron probe then returns to the reference point by travelling down a line. The raster on the sample is made using a scan generator connected to the scanning coils. The process continues until the image is formed.

2.2 Basics of SEM imaging

The electron probe spends a brief amount of time at each pixel to collect intensity data to create an SEM image. This period is known as "dwell time" (T_d). With the aid of dwell time, we can calculate the amount of time needed to scan a row(T_r) and an entire frame scan time(T_f) which can be calculated using the following equations:

$$T_r = wT_d + T_j \tag{2.1}$$

$$T_f = hT_r = hwT_d + hT_j \tag{2.2}$$

where :

w = count of pixels in a row

h = count of pixels in a column

T_j = amount of time required to maintain and reposition the electron probe before starting the subsequent row scan.

Since each pixel is captured at a distinct moment, we may relate each pixel's location (x, y) to the time the electron beam scanned it, which can be expressed as:

$$T(x, y) = xT_d + yT_r \tag{2.3}$$

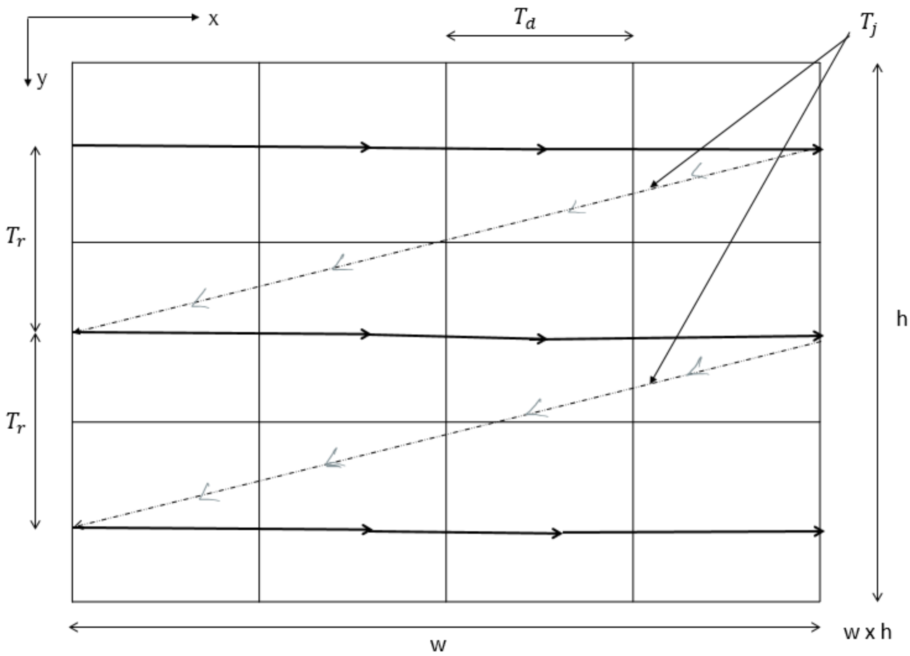


FIGURE 2.2: Raster scanning process

2.3 Artifacts of SEM imaging

SEM imaging artifacts, are as follows:

1 - Scan line shift

2 - Drift Distortion

3 - Spatial Distortion

These artifacts can be understood with the help of figure 2.3 and 2.4:

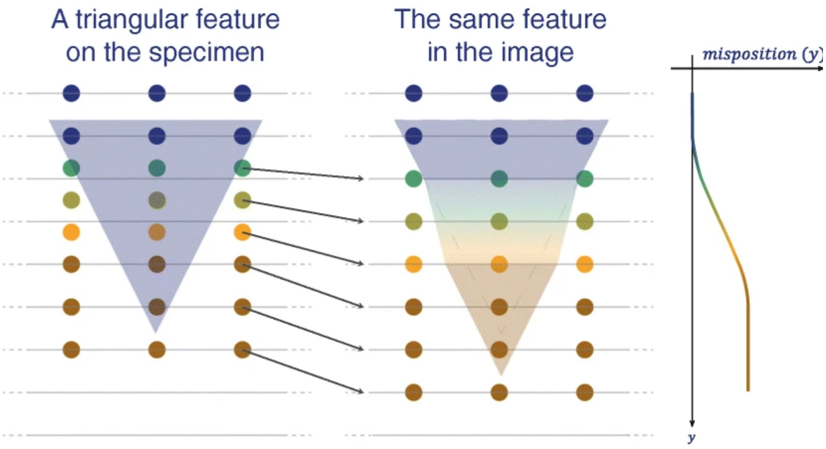
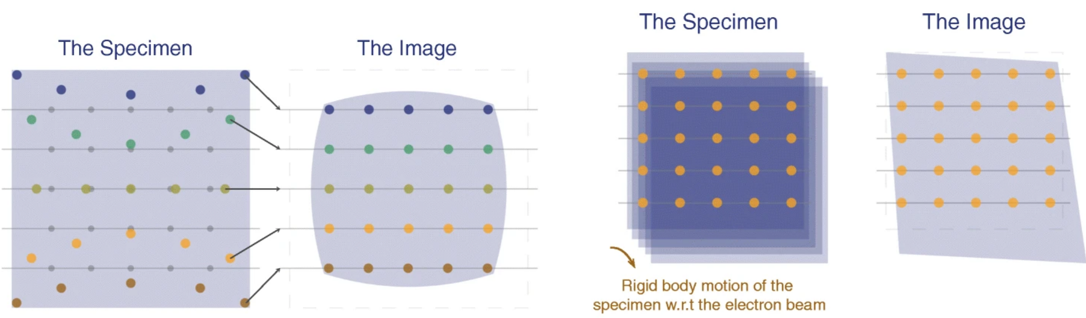


FIGURE 2.3: Scan Line Shift [7]



(a) (b)

FIGURE 2.4: (a) Spatial distortion and (b) Drift distortion [6]

Chapter 3

Digital Image Correlation

The digital image correlation, often known as DIC, is a non-contact optical approach to quantifying strain maps and full field displacements. Both 2D and 3D displacements can be calculated using Digital Image Correlation (DIC). Comparing digital images taken of the same component at varying phases of deformation is the core of DIC's methodology. The DIC approach generates a full field strain map by monitoring each pixel location and detecting surface deformations to obtain 2D and 3D displacements. The pixels of SEM images have various intensity values and are arbitrary and distinct for the DIC procedure to be efficient. The original specimen's surface often has adequate image texture enabling DIC to function without specific surface preparation.

3.1 Basic Concepts behind DIC Technique

An SEM machine is used to produce two images of the specimen's surface, one before and one after the deformation, and then uses the DIC approach to correlate these images. The first picture is known as the reference picture, while the second picture is known as the current picture. In a nutshell, the application of the two dimensional DIC approach may be broken down into the three sequential processes that are detailed below:

1 - The samples are prepared using a speckle pattern.

2 - The SEM device captures photographs of the sample's surface(flat) before and after the application of the load.

3 - Full field displacements and the strain maps can be obtained by processing the photos with the help of computer software

By sprinkling paint in either black or white, we may produce a random speckle pattern on sample's surface. Utilizing the natural texture of the surface is another viable option for us. The illustration 3.1 depicts the basic image recording setup layout.

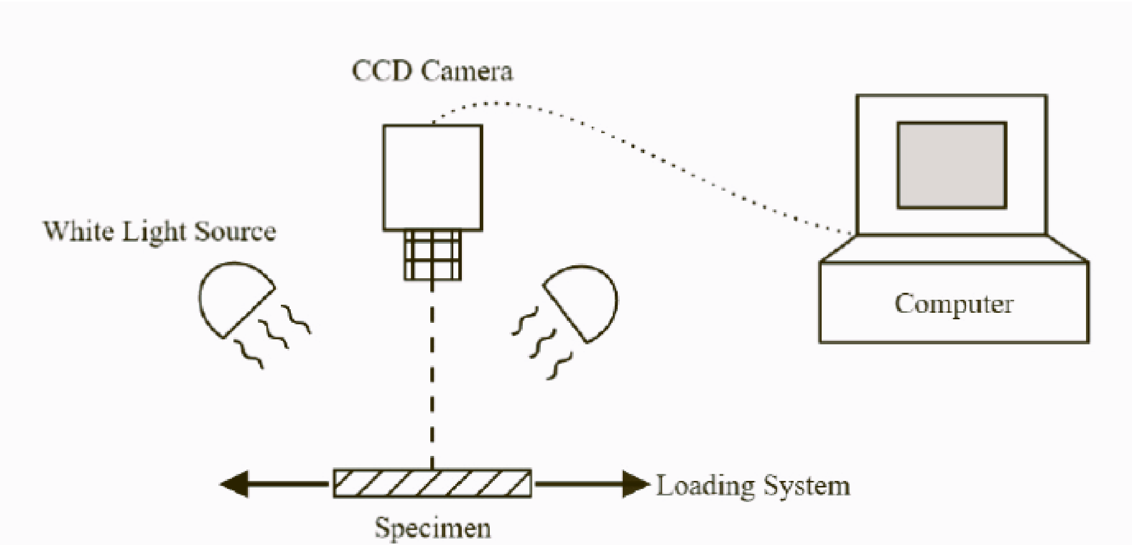


FIGURE 3.1: Image recording setup layout [3]

Photographs of the specimen's surface are taken with a digital camera. Figure 3.1 shows that the optical axis of the digital camera is perpendicular to the sample's surface and parallel to the charge-coupled device-sensor(CCD) target. The specimen should only move in the plane in which it is being examined.

Assume that a point (x_r,y_r) in the reference picture corresponds to a point (x_d,y_d) in the distorted image. In that situation, it is assumed that the intensities of the pixels do not change while the body deforms. If I and $I^{'}$ are the intensities functions for reference and distorted configurations, respectively, then :

$$I(x_r, y_r) = I^{'}(x_d, y_d).$$

A specific intensity value(integer) is assigned to each pixel location on the sample's surface, ranging from 0 to 255. The main idea behind two-dimensional digital image correlation is to look for the same pixels in the two pictures captured before and after deformation. The reference subset extracted from the reference image is displayed in left of Figure 3.2. We should extract the subdomain in such a way that it should be a square subset with a size of (2m+1) × (2m+1). The deformation of this subset depicted in right of the Figure 3.2. There is a connection between the point N in the reference subset and the center of the

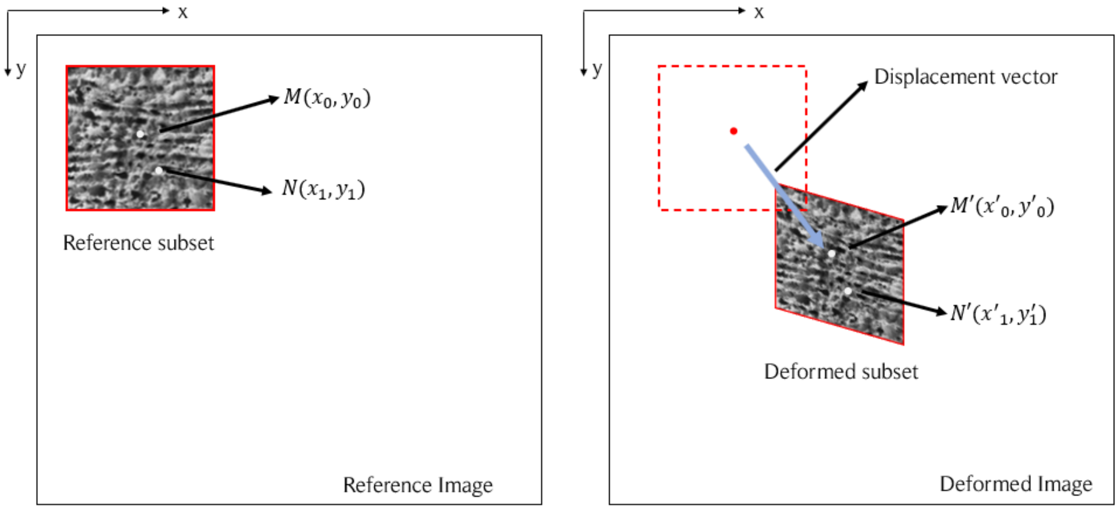


FIGURE 3.2: The reference subset extracted from the reference image is displayed in left of figure, and the deformation of this reference subset depicted in the right of the Figure [1]

subset M. Assuming that the coordinates of the center point M are (x_0,y_0), we can give the coordinates of point N as :

$$\begin{aligned} x_1 &= x_0 + \Delta x \\ y_1 &= y_0 + \Delta y. \end{aligned} \tag{3.1}$$

If the displacements of the center point are u_0 and v_0 then the coordinates of point $M^{'}$ in the deformed subset can be given as:

$$\begin{aligned} x_0^{'} &= x_0 + u_0 \\ y_0^{'} &= y_0 + v_0. \end{aligned} \tag{3.2}$$

With the help of equation 3.1 and equation 3.2, the coordinates of point $N^{'}$ in the deformed subset can be given as:

$$x_1^{'} = x_1 + u_0 + \frac{\partial u}{\partial x}(x_1 - x_0) + \frac{\partial u}{\partial y}(y_1 - y_0). \tag{3.3}$$

$$y_1^{'} = y_1 + v_0 + \frac{\partial v}{\partial x}(x_1 - x_0) + \frac{\partial v}{\partial y}(y_1 - y_0). \tag{3.4}$$

From equation 3.3 and equation 3.4, we can understand that there are six quantities $u_0, v_0, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}$ that needs to be determined. Each of the six quantities for a particular subset is unknown.The optimum solution for these six quantities can be obtained by finding the highest correlation between the intensities of pixels in the reference subset and the intensities of pixels in the deformed subset.

The correlation can be measured with the following equation 3.5:

$$C = \frac{\sum_{(2m+1)\times(2m+1)}[I(x_r, y_r) - I^{'}(x_d, y_d)]}{\sum_{(2m+1)\times(2m+1)}[I^2(x_r, y_r)]}. \tag{3.5}$$

The analysis is performed in an organised fashion utilising the Newton-Rapson's algorithms that are outlined in the paper [2].

We have produced two photos from the SEM instrument(figure 3.3) to help you understand the DIC process and outcomes. These photos' specifications are as follows:

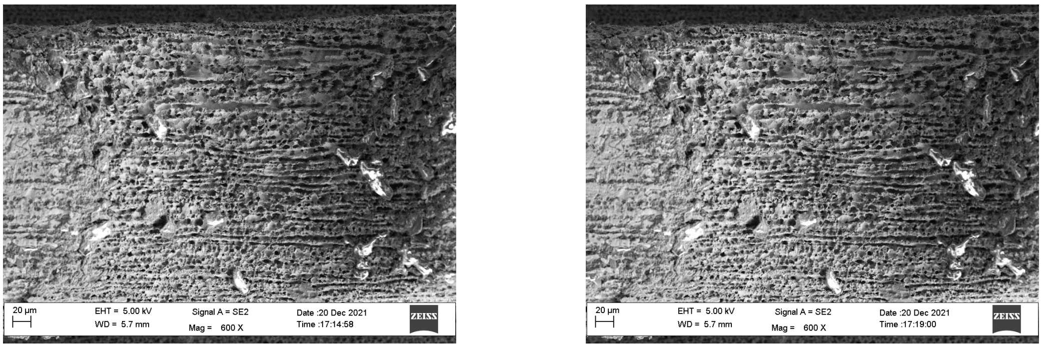
* The magnification at which images of a steel sample were captured - 600 $\times$

* Scan speed at which images are taken = 8

* The rigid body motion applied in between these two images in x-direction = 11.3 μm

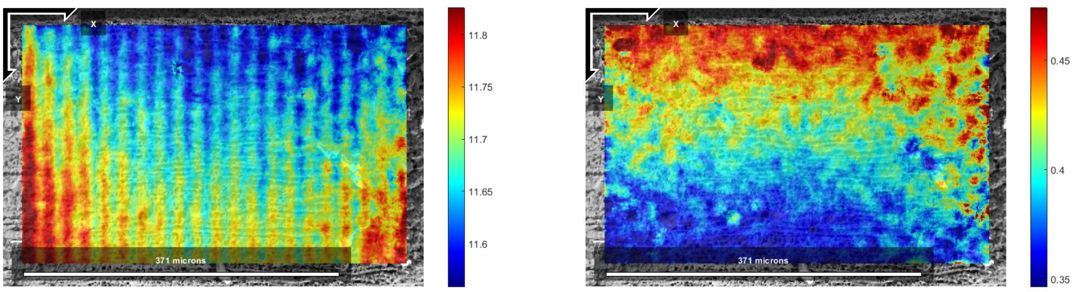
* The rigid body displacement data obtained from SEM in between these two images in y-direction = 0.5 μm

Between these two images of the steel specimen, the digital image correlation methodology is used. As depicted in Figures 3.4(a) and 3.4(b), we receive data on both U-displacement and V-displacement. On the right of the Figures 3.4(a) and 3.4(b), a rectangular colour bar is visible. The distribution of displacements at various pixels is displayed by this rectangle bar. It is clear to observe that the U-displacement ranges from 11.6 to 11.8μm and V-displacement ranges from 0.35 to 0.45μm. Clearly, the data collected using the DIC procedure and the SEM machine are distinct. The primary cause of this distinction is the artifacts (i.e., spatial distortion and drift distortion). In the following chapter, a generic implementation technique for the distortion calibration step to measure drift distortion and spatially changing distortion is described.



(a) (b)

FIGURE 3.3: (a) Reference image taken at 600 × (b) Current image taken at 600 ×



(a) (b)

FIGURE 3.4: (a)U-displacement obtained by DIC (b) V-displacement obtained by DIC

Chapter 4

Correction of Drift and Spatial Distortion

In an SEM image, a position is deformed as a result of spatial and time-varying distortions. Therefore, we must define the spatially-varying and drift distortion functions in order to determine the distorted location in the deformed configuration. Let's say spatial distortion function is denoted with the symbol $\boldsymbol{D_s}(x, y)$ and the drift distortion function is denoted by the symbol $\boldsymbol{D_d}(\mathrm{T})$ where T is defined as the scan time and (x, y) denotes the pixel location.

As shown in figure 4.1, in the reference configuration, a point M at $\boldsymbol{R_{ud}}$ is undergoing a deformation to map onto a point M' at $\boldsymbol{\zeta} = \boldsymbol{R_{ud}} + \boldsymbol{u}$ in the deformed configuration. $\boldsymbol{R_{ud}}$ represents the location of point M in terms of its undistorted pixel value. In addition to mechanical deformation, drift and spatial distortion also cause the point to deform further to map onto a point M" at $\boldsymbol{R_d}$. Therefore, the location of the same point, in its distorted state is expressed as:

$$\boldsymbol{R_d} = \boldsymbol{R_{ud}} + u\boldsymbol{D_d}(T) + \boldsymbol{D_s}(x, y). \tag{4.1}$$

Since distorted locations can be measured with the help of various tests, they can be obtained during the calibration process. The scanning electron microscope (SEM) approach relies on the atomic interaction between an observed sample and an electron ray, as well as techniques of scanning and focussing that make use of electromagnetic ideas to carry out the necessary duties. Because of this, traditional approaches that are intended to rectify spatial distortion are unsuccessful. This thesis talks about a way to fix distortion with the help of calibration phase.

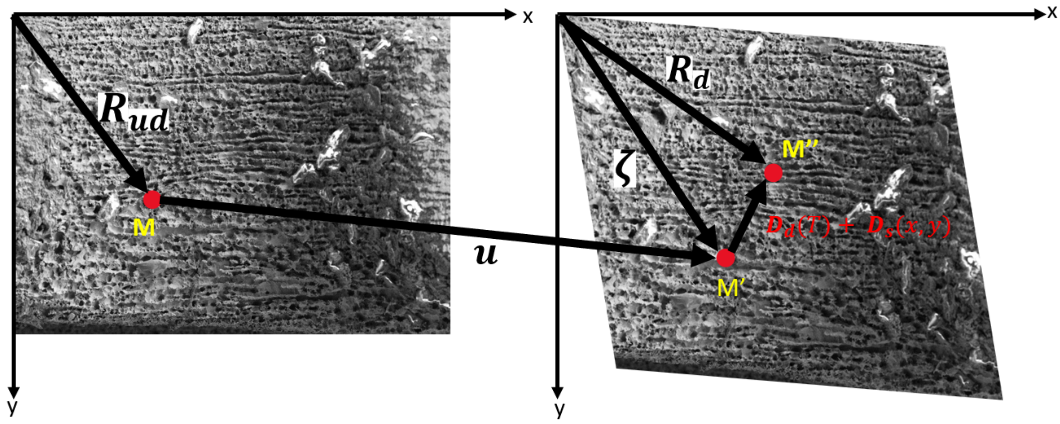


FIGURE 4.1: Due to mechanical deformation, point M in the reference configuration maps to point M' in the deformed configuration. But drift and spatial distortion also cause the point to deform further to map onto a point M"

4.1 Calibration phase used to correct Distortions

The position of the pixel can have an effect on the amount of spatial distortion. So, developing a connection between spatially varying distortion and displacement is the primary goal of this calibration phase.

The steps outlined below constitute a calibration procedure:

(i) - Acquire photos for use in the calibration process in a particular manner.

(ii) - The time-varying distortion will be present in the acquired images. Get rid of these aberrations with the assistance of the appropriate procedure.

(iii) - Designate a connection between the spatial distortion and the displacement, such as a plot of the spatial distortion vs the displacement.

The following steps outlines the general scanning procedure for the calibration phase:

(i) A specimen is given a speckle pattern in order to make the images (produced by the SEM) suitable for DIC.

(ii) It is then essential to obtain a series of image pairs, with the specimen remains in the same place during the scanning of each pair. The pair of images are numbered as (i-1,i) where i = 2,3,4,...N; N = total no of images captured during the calibration phase 4.2 .

(iii) In between the capture of each pair of images, rigid body motions are applied, which means that the specimen is moved with a known distance in both X-direction(horizontal) and Y-direction (vertical) see figure 4.3 .

Figure 4.2 displays a series of photographs obtained during the calibration period, organised into nine pairs or groups numbered as 1,2,3,..9. Any particular image pair suggest that, only time-varying distortion is evident between the two pictures of that particular image pair because they were captured while the sample was kept immobile. We can accurately analyse spatial distortion and expedite the calibration procedure with the aid of such 2D movement of specimen(figure 4.3). About one-fourth of the FOV should be covered by the combined X and Y translation. Consequently, each stationary pair is utilised in the estimation of the drift distortion. When comparing translating images, such as images one and three, there is evidence of drift distortion and spatially varying distortion. The odd-numbered photos are correlated in order to determine the amount of spatially-varying distortion between them after stationary pairs have been rectified for any time-varying aberration present in the images.

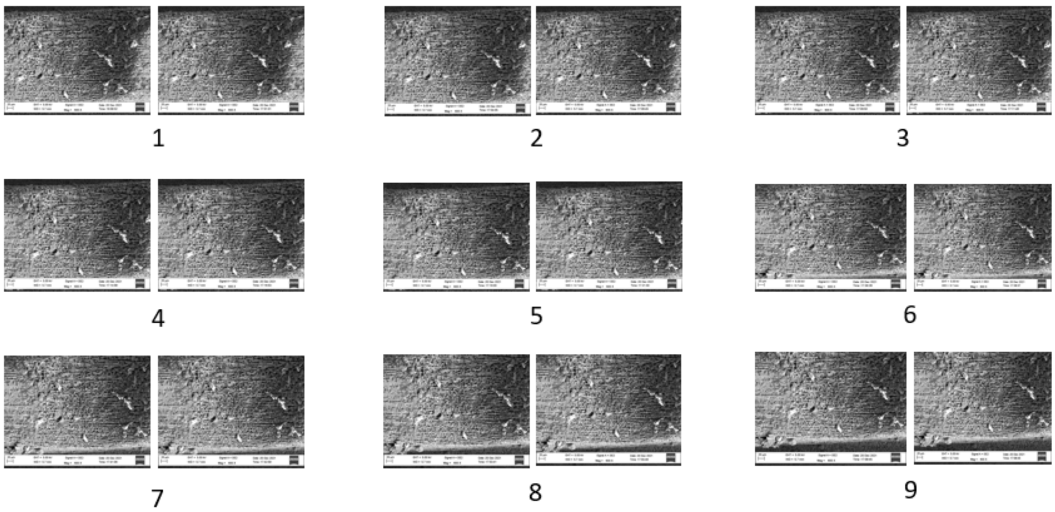


Figure 4.2: A series of photographs obtained during the calibration period, organised into nine pairs or groups numbered as 1,2,3,..9.

The expression for the time-varying distortion function can be defined as:

$$\boldsymbol{D_d}(T) = [d_X(T), d_Y(T)], \tag{4.2}$$

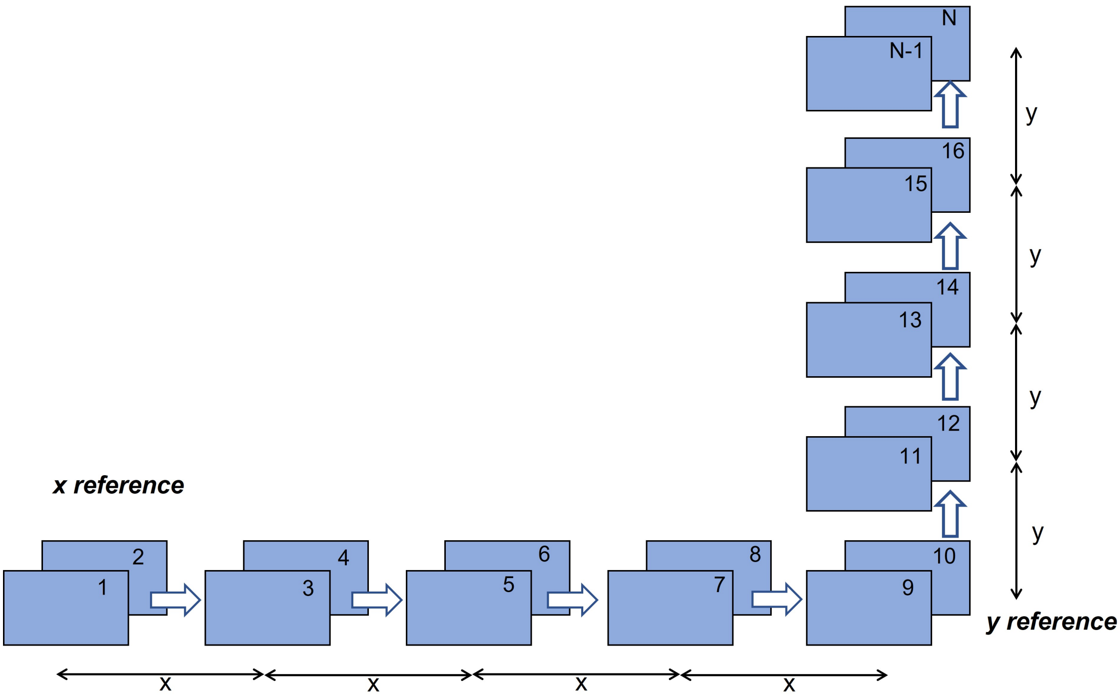


FIGURE 4.3: The chronology in which images are captured during the calibration phase [11]

where $d_X(T)$ is defined as horizontal drift and $d_Y(T)$ is defined as vertical drift. Time 'T' is defined as the scan time(see equation 2.3) for a pixel position (x, y) in an SEM image.

We know, according to equation 2.3, that the amount of time required to scan any particular pixel may be expressed as:

$$T(x, y) = xT_d + yT_r,$$

where $0 \leq y \leq h - 1$ and $0 \leq x \leq w - 1$.

So, The total amount of time spent throughout the calibration scanning procedure, for a specific pixel location(x,y), can be expressed as:

$$T_t(x, y, i) = T_{t,i} = xT_d + yT_r + (i - 1)(T_f + \Delta T_i), \tag{4.3}$$

where i = 1,2,3,4,...N; N = total number of captured images during the calibration phase. ΔT_i is the amount of time that has elapsed between (i-1) and the i-th image.

Suppose an object point M is situated in the plane of an image at time T and coordinates (x, y). Because of drift, the same object point moves to a new location M' at time $T + \Delta$.

The drift disparity, denoted by the notation $\boldsymbol{disp_d}$(x, y), is defined as the difference in locations for a single object point. In order to obtain the displacement data, we perform the DIC procedure between the images of a pair(i.e., image (i-1) and image(i)). We can calculate the drift disparity for each fixed location (x, y) in the detector plane using displacement data obtained from the DIC, which the following equation can express.

$$\boldsymbol{disp_d} = \boldsymbol{D_d}(T + \Delta) - \boldsymbol{D_d}(T), \tag{4.4}$$

where

$$\Delta = T_f + \Delta T_i + T_{disp}. \tag{4.5}$$

and

$$T_{disp} = [d_X(T + \Delta) - d_X(T)]T_d + [d_Y(T + \Delta) - d_Y(T)]T_r. \tag{4.6}$$

An illustration of the procedure, established by equations 4.2, 4.4, 4.5, and 4.6, is shown in Figure 4.4. Experiments show the shift between photos, which is quite easy to spot because the drift for location (0, 0) in the following image is very different from the drift for location (w-1, h-1) in the previous image(see Figure 4.4). The dotted red line shows the optimal linear fit.

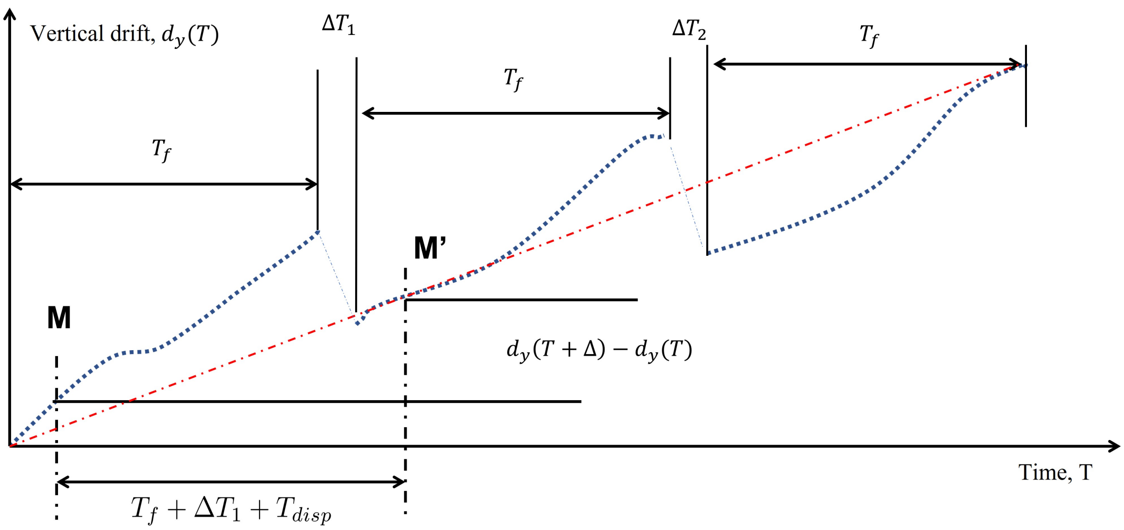


FIGURE 4.4: A three-image example that shows noise free vertical drift as a function of time along with the concept of disparity [11]

It is possible to make an evaluation of the time-varying velocity, $\boldsymbol{V_d}$ $(x, y; T + \Delta/2)$, for each location by applying central finite difference form. So the drift velocity in X and Y direction can be given as:

$$\boldsymbol{V_{d_X}}(T + \Delta/2) = \frac{[d_X(T + \Delta) - d_X(T)]}{\Delta}. \tag{4.7}$$

$$\boldsymbol{V_{d_Y}}(T + \Delta/2) = \frac{[d_Y(T + \Delta) - d_Y(T)]}{\Delta}. \tag{4.8}$$

The images(1,3,5,7,.., N-1) are required to get the drift distortion function, $\boldsymbol{D_{d,i}}$ (x, y), which is then used to rectify the corresponding images. To obtain the drift distortion function, $\boldsymbol{D_{d,i}}$, at each (x, y) point in the i-th odd-numbered images, a time-integrated B-spline curve is fitted to the time-varying drift distortion velocity, $\boldsymbol{V_d}$ $(x, y; T + \Delta/2)$, at each location (x, y) . The time-varying distortion for each location can be calculated by integrating the B-spline curve for $\boldsymbol{V_d}(x, y; T)$ across time with the help of initial condition $\boldsymbol{D_d}(0, 0) = (0, 0)$ at T = 0.

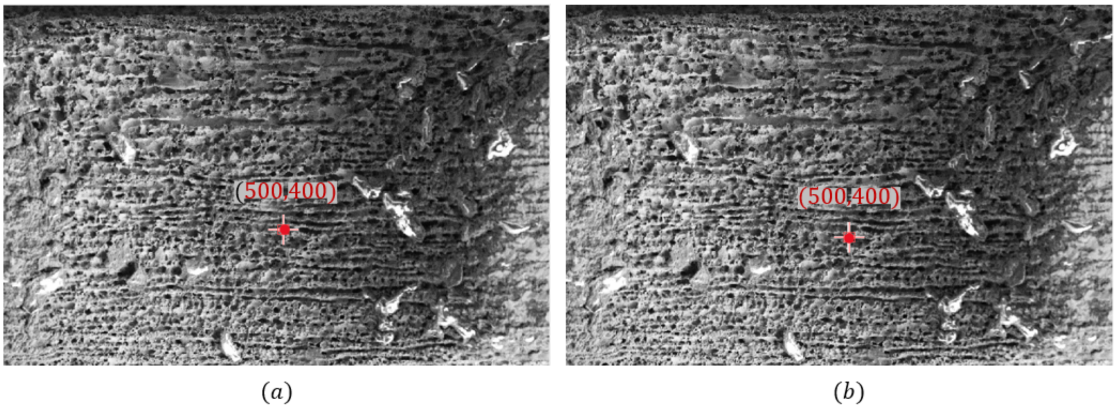


FIGURE 4.5: Two images of a stationary pair having exact pixel location, taken at two different times. Due to the drift, the pixel location changes in the image (b)

We have taken a pixel location (500,400) as shown in figure 4.5 and at this pixel location, the drift velocity in X-direction ($\boldsymbol{V_{d_X}}(T + \Delta/2)$) is fitted with a B-spline curve over the total time elapsed to capture the calibration images as shown in figure 4.6.

Similarly, at the pixel location (500,400), the drift velocity in Y-direction ($\boldsymbol{V_{d_Y}}(T + \Delta/2)$) is fitted with a B-spline curve over the total time elapsed to capture the calibration images as shown in figure 4.7.

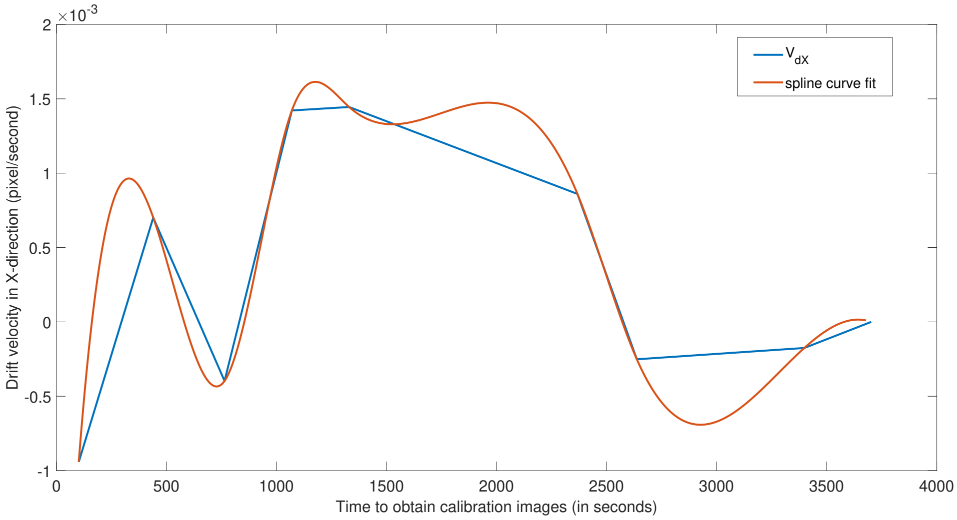


FIGURE 4.6: At pixel location (500,400), B-spline curve is fitted to drift velocity in X-direction over the total calibration time

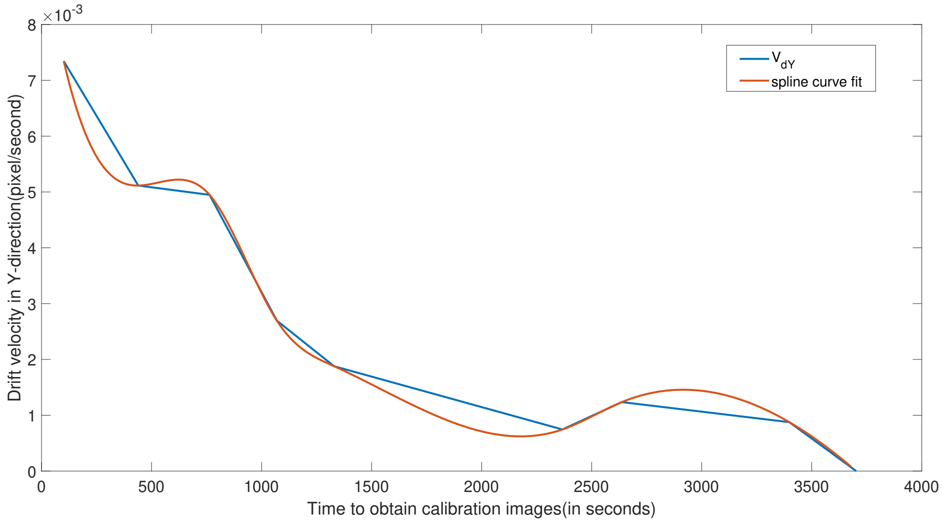


FIGURE 4.7: At pixel location (500,400), B-spline curve is fitted to drift velocity in Y-direction over the total calibration time

As we have removed the drift from these images, we can now determine the amount of spatially-varying distortion present in each odd-numbered frame.

To obtain the spatial distortion, the following steps are required:

1 - With the help of DIC, correlate the odd-number images which have previously been drift-corrected.

2 - Get the DIC method's displacement data set $(\boldsymbol{U}, \boldsymbol{V})$ and input displacement data set (u_{input}, v_{input}) given in the calibration phase between the SEM images with odd numbers.

3 - If the expression for the spatially-varying distortion function is defined as:

$$\boldsymbol{D_s}(x, y) = [s_X(x, y), s_Y(x, y)]. \tag{4.9}$$

then the spatial distortion in both the orthogonal directions can be calculated as :

$$s_X(x, y) = \boldsymbol{U(x, y)} - u_{input}. \tag{4.10}$$

$$s_Y(x, y) = \boldsymbol{V(x, y)} - v_{input}. \tag{4.11}$$

The rigid body motion is applied between the each stationary image pairs in X-direction. For the pixel location (500,400) as shown in figure 4.5, the connection between the spatial distortion and the applied displacement in X-direction, such as a plot of the spatial distortion vs the applied rigid body displacement is shown in figure 4.8.

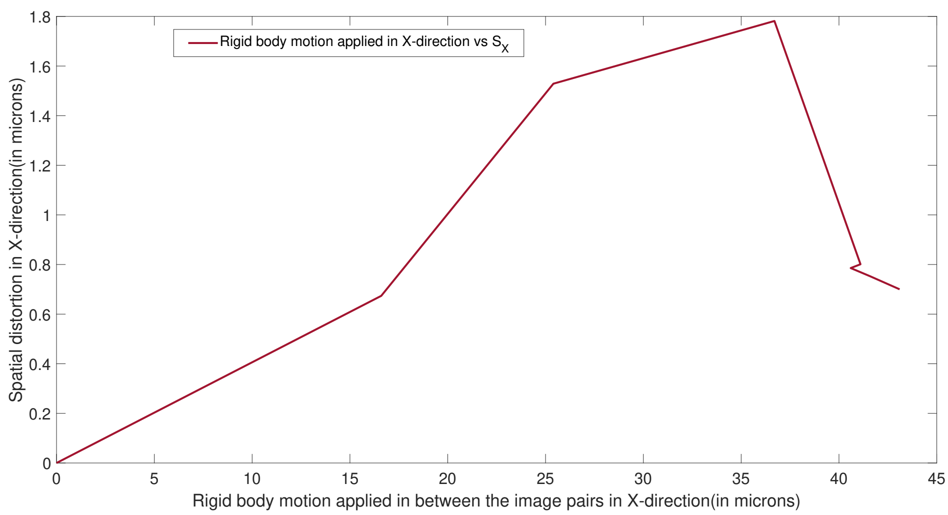


FIGURE 4.8: For the pixel location (500,400), the plot of rigid body motion applied in X-direction vs. spatial distortion in X-direction is plotted here.

The rigid body motion is applied between the each stationary image pairs in Y-direction. For the pixel location (500,400) as shown in figure 4.5, a plot of the spatial distortion vs the applied rigid body displacement in Y-direction is shown in figure 4.9.

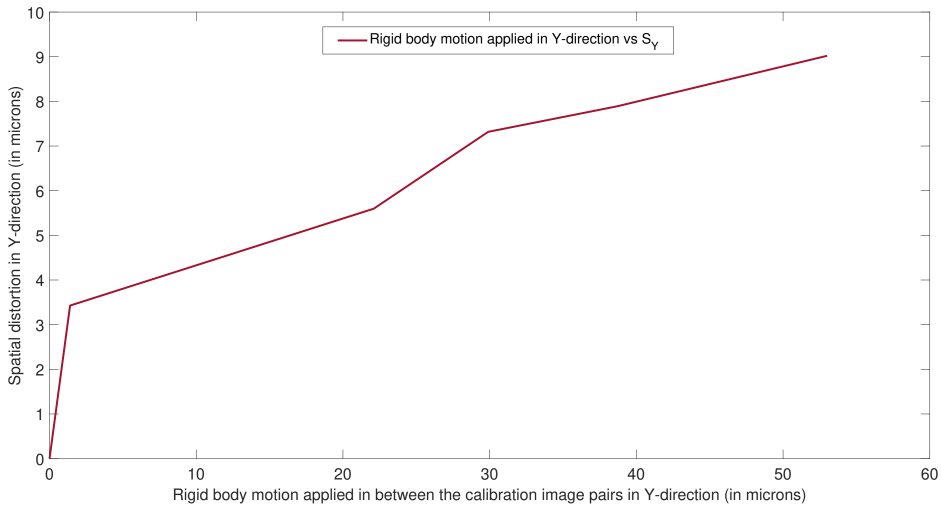
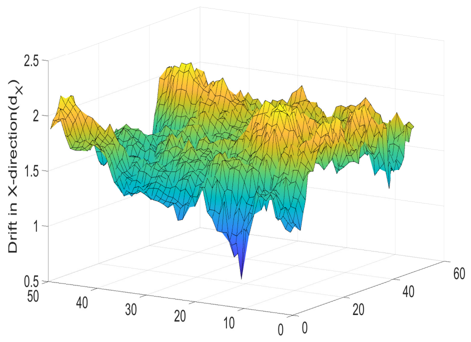
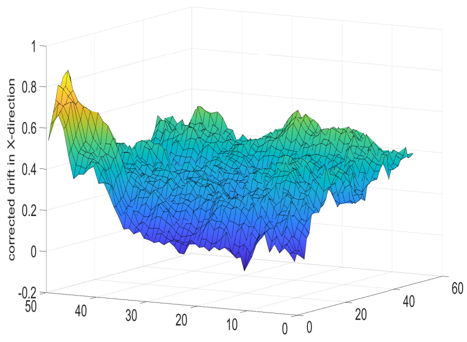


FIGURE 4.9: For the pixel location (500,400), the plot of rigid body motion applied in Y-direction vs. spatial distortion in Y-direction is plotted here.

Images are correlated at a finite number of pixel positions, and the collected data at those locations are interpolated to obtain the data at each position. In order to do correlation, a group of 50 $\times$ 50 pixels are collected, and correlation is done throughout the entire 957 $\times$ 619 sized image. With the help of calibration technique, the drift and spatial distortions are eliminated to perform an effective DIC. The drift in X-direction and the correction of the drift in X-direction can be seen in figure 4.10. The drift in Y-direction and the correction of the drift in Y-direction can be seen in figure 4.11.

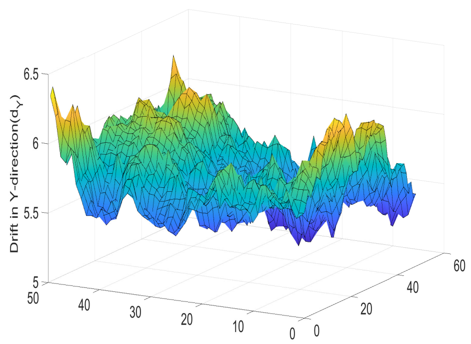


(a)

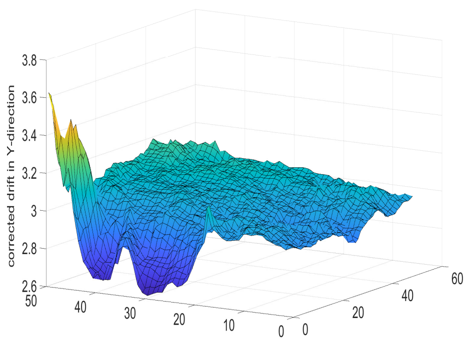


(b)

FIGURE 4.10: (a) Uncorrected drift in X-direction and (b) corrected drift in X-direction



(a)



(b)

FIGURE 4.11: (a) Uncorrected drift in Y-direction and (b) corrected drift in Y-direction

The overall method used to rectify distortion in a SEM can be understood with the help of figure 4.12.

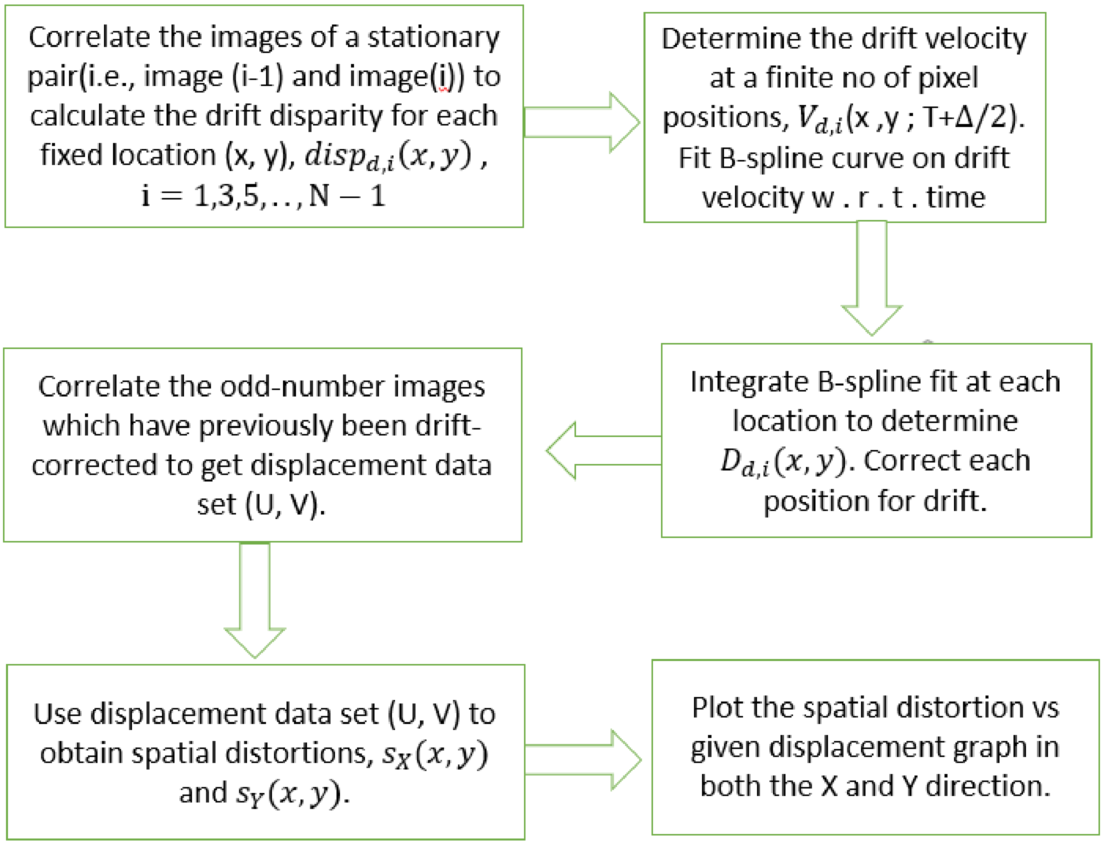


Figure 4.12: The overall method used to rectify distortion in a SEM. [11]

The deformation experiment can be carried out inside an SEM under various conditions. However, how the SEM imaging process works, obtaining full-field displacements and strain maps within an SEM, is complicated. We have demonstrated that attempts to employ DIC-based approaches to compute displacements can fail due to distortions produced by the raster scanning process through which the electron beam forms a digital image. These distortions can cause the computation of displacements to be inaccurate. In this thesis we have discussed recently developed approaches for correcting spatial and drift aberrations in SEM images. To do so, we have used calibration technique and calculated & removed these artifacts to perform an effective DIC.

Appendix A

Drift and spatial correction code manual

Main File

Steps

1. Input Basic SEM machine data
2. Loading and cropping of calibration images
3. Computing the disparity data through DIC
    (i) Between the images of stationary pairs for drift calculation
    (ii)Between the images of moving pairs for spatial distortion calculation
4. Computing the time matrix
5. Computing the Drift Velocities in both X and Y direction
6. Data input of rigid body motion given in both X and Y direction
7. Computing the Drift distortion in both X and Y direction
8. Computing the Spatial distortion in both X and Y direction

Description of variables

T_d: dwell time taken by machine, to define the intensity of image at each pixel location

T_r: time required to scan an entire row

T_f: time required to scan an entire frame

T = scan time for any given pixel location in an image

T_t: time required to scan all the calibration images

t_1: it's a part of T_t which accounts for the scan time of odd-numbered images

t_2: it's a part of T_t which accounts for the scan time of even-numbered images

$T_{elapsed}$: average of t_1 and t_2

A: multidimensional array of original images

C: multidimensional array of cropped images

U: disparity data obtained between stationary pairs in X-direction

V: disparity data obtained between stationary pairs in Y-direction

U2: disparity data obtained between moving pairs in X-direction

V2: disparity data obtained between moving pairs in Y-direction starttime: the time after which any particular image is ready to be scanned

endtime: the time at which any particular image is fully scanned

delay_time: time elapsed between one image scan and the next image scan

Vx: drift velocity in X-direction

Vy: drift velocity in Y-direction

Given_x: Applied rigid body motion in X-direction

Given_y: Applied rigid body motion in Y-direction

csgx: cumulative sum of Givenx

csgy: cumulative sum of Giveny.

function - crop_tool

function [C] = crop_tool(n,A)

This function takes the original images(A) and crop all of them into same size and save it in C.

function - calibration_input

function[C] = calibration_input(xlsfname)

(input: xlsfname)

It is the name of an excel file which contains the calibration data obtained from the SEM machine such as image no., full path location of the original calibration image, starttime, endtime, delaytime, applied rigid body motion in X-direction and applied rigid body motion in Y-direction.

(output: C)

Successfully obtained and cropped all images in the directory.

function - disparity_calc

function[U,V,U2,V2] = disparity_calc(C)

(input: C)

C is the cropped calibration images, used to obtain region of interest in an image and to perform DIC between stationary pairs and moving pairs.

(output1: U)

Disparity data is obtained between stationary pairs in X-direction. It is used to obtain drift distortion in X-direction.

(output2: V)

Disparity data is obtained between stationary pairs in Y-direction. It is used to obtain drift distortion in Y-direction.

(output3: U2)

Disparity data is obtained between moving pairs in X-direction. It is used to obtain spatial distortion in X-direction.

(output4: V2)

Disparity data is obtained between moving pairs in Y-direction. It is used to obtain spatial distortion in Y-direction.

function - calc_timematrix

function[T_t,T_elapsed] = calc_timematrix(C,endtime,delay_time,starttime,basic_data)

This function is used to compute time required to scan all the calibration images and average of t_1(scan time of odd-numbered images) and t_2(scan time of even-numbered images). It takes all the input data from the excel file named xlsfname.

function - drift_velocity

function [Vx,Vy] = drift_velocity(C,U,V,basic_data,starttime,endtime)

This function is used to calculate drift velocity in X and Y-direction. The basic data values for the calculation of Vx and Vy are T_d, T_r, and T_f. Drift velocities are used to find the drift distortions.

function - drift_integrate_main

function [driftx,drifty] = drift_integrate_main(pixelx,pixely,upto_time,T_elapsed,Vx,Vy)

This function is used to calculate drift distortion in X and Y-direction. To obtain the drift distortion at each $(pixelx, pixely)$ location in the odd-numbered images, a time-integrated B-spline curve is fitted to the time-varying drift distortion velocity, at each location (x, y) . The time-varying distortion for each location can be calculated by integrating the B-spline curve across time. It also generates the plot of fitted B-spline curve on drift velocities over time.

function - spatial_distortion

function [spatialx,spatialy] = spatial_distortion(A_csx,B_csy,driftx,drifty)

This function is used to calculate spatial distortion in X and Y-direction. A_csx is the cumulative sum of csx for a given image pair and B_csy is the cumulative sum of csy for a given image pair.

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