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Correction of scan line shift artifacts in scanning electron microscopy - an extended digital image correlation framework

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Abstract

High Resolution Scanning Electron Microscopy (HR-SEM) is nowadays very popular for different applications in different fields. However, SEM images, may exhibit a considerable amount of imaging artifacts, which induce significant errors if the images are used to measure geometrical or kinematical fields. This error is most pronounced in case of full field deformation measurements, such as Digital Image Correlation (DIC). One family of SEM artifacts result from positioning errors of the scanning electron beam, creating artifactual shifts in the images perpendicular to the scan lines (scan line shifts). This leads to localized distortions in the displacement fields obtained from such images. This type of artifacts is here corrected using global DIC (GDIC). A novel GDIC framework, considering the nonlinear influence of artifacts in the imaging system, is introduced. Using an enriched regularization in the global DIC scheme, based on an error function, the line shift artifacts are captured and eliminated. The proposed methodology is demonstrated in virtually generated and deformed images as well as real SEM micrographs. The results confirm the proper detection and elimination of this type of SEM artifacts.

Keywords: Scanning electron microscopy, Imaging artifacts, Artifact correction, Line shift artifact, Microscopy measurements, Global digital image correlation.

1 Introduction

Scanning electron microscopy (SEM) has proven itself to be one of the most powerful microscopy methods available. It offers a high spatial resolution (e.g. compared to light mi-
croscope) and relative ease of use (e.g. with respect to transmission electron microscopy).

Besides qualitative studies based on SEM images of different materials, quantitative information can be extracted from them as well. Examples of quantitative measurements of in-plane geometrical properties may be found in different fields, such as nanocomposites (Kang et al., 2012; Brodusch et al., 2015), micro residual stress measurements (Lord et al., 2010), biomedical engineering (Bellani et al., 2016; Gu et al., 2016) and microscopy methods (Mussa et al., 2013; Jones et al., 2014). Comparative studies between more than one image introduces another level of quantitative analysis on SEM images. Advanced quantitative measurements go as far as full field displacement measurements based on digital image correlation (DIC) using SEM images in experimental micromechanics (Sutton et al., 2009; Sutton and Hild, 2015; McCormick and Lord, 2010). However, using SEM images for a quantitative geometrical measurement becomes problematic if several complicated imaging artifacts occur (Postek and Vladár, 2013; Postek et al., 2013). These artifacts result in distortions in the image, leading to errors in measurement of the underlying geometrical or kinematical fields. Such distortions induce artifactual deformations and strains in DIC measurements, constituting significant errors if ignored. Due to the sensitivity of full field displacement measurements to these errors, caused by artifactual displacement fields, the DIC community is very concerned with the treatment of such imaging artifacts.

The SEM imaging artifacts can be categorized into three types (Sutton et al., 2009). The first type is non-random, time-independent spatial distortion, which is similar to distortions observed in optical systems. A number of papers propose different methods
for dealing with this type of artifact (Sutton et al., 2006, 2007a; Guery et al., 2014). The second category is non-random, time-dependent distortion (referred to as drift), which triggers stretch/compression or shear distortions in image. This is a direct result of the scanning involved in the SEM imaging process (Postek et al., 2014). Different methods for correcting this artifact are proposed in the literature for SEM images (Sutton et al., 2006, 2007a; Cizmar et al., 2011; Schajer et al., 2013) and other microscopy methods involving a similar scanning process (Meyer et al., 2014; Ophus et al., 2016). The third type is a random, time-dependent distortion which is due to positioning errors of the electron beam during scanning referred to as “scan line shifts”. Lagattu et al. (2006) reported the presence of such artifacts, in the form of local peaks parallel to the scan lines in strain maps of SEM-DIC. Sutton et al. (2007b) conducted an extensive study on this artifact, which induces jumps in the displacement maps obtained by DIC. The effect of scanning parameters in four SEMs from different manufacturers is studied in their work. Integrating a collection of images is a solution proposed to limit the influence of the shifts. Integration of eight images removed the artifact to a good extent, for shifts up to one pixel. The scan line shift artifact has been studied far less than the other types. Hence, there is still a need for a robust method to deal with this type of artifact. This paper proposes a systematic method to resolve the scan line shift artifact for SEM images, applicable to any imaging technique involving a scanning process.

Let’s consider the scan line shift artifact in more detail. Figure 1 exhibits a clear scan line shift in an SEM image. On the left in figure 1(a) an SEM image of a dual phase steel with a field of view of 30µm is presented. On the right, a zoomed view of the
same image is compared to the zoomed view of another SEM image, scanned immediately after the first one (showing the same region). No mechanical displacement was applied to the specimen between the two consecutive scans. The left image contains a line shift which is an artifact of the scanning process. This shift is highlighted in Figure 1(a) by the indicators showing the lower half of the feature moving downwards in the zoomed image on the right. Figure 1(b) shows the displacement in the vertical direction found by standard local DIC between the two aforementioned SEM images. Two distinct jumps in the displacement field, one positive and one negative, are visible, occurring at certain \( y \) values and constant for all \( x \) values (\( y \) is the vertical coordinate perpendicular to scanning direction, and \( x \) is the horizontal scanning direction).

The occurrence of scan line shifts originates from the SEM imaging process. An SEM image is generated by scanning an electron beam point by point on the surface of the specimen and gathering the electrons that are emitted from the surface, due to the interaction of the electron beam and the specimen, by different sensors. Since the positioning of the beam during the scanning cannot be controlled by a closed loop, positioning errors are inevitable. This error is a high frequency phenomenon if occurring between pixels in the same row in an image, thus contributing to the noise. However, if such a positioning error occurs between two consequent scanning lines, a low frequency phenomenon, it becomes detectable as a shift in the image, e.g. see in figure 1(b). The repositioning of the electron beam in the direction perpendicular to the scanning direction is done once per scan line. Hence, an error in this direction persists until the end of that scan line and subsequently propagates to the next line. This type of artifact therefore reveals an artificial band of
localized distortion along the scanning direction in the image.

The aim of the current work is to develop a framework to deal with the scan line shifts in SEM images using a systematic approach. This enables: (i) direct removal of shifts from images, (ii) integration with other methods available in the literature, for correction of drift and spatial distortion artifacts, (iii) future extension of the method to a general framework dealing with all types of SEM artifacts. To this end, global digital image correlation (GDIC) is used in a general framework in order to deal with the scan line shift artifact.

In GDIC the deformation field relating two subsequent images is directly determined in the whole region of interest of the images. This is done by prior knowledge on the kinematics characterizing the deformation, i.e. regularizing the displacement field. Using a proper regularization of the displacement field it is possible to identify and correct the scan line shift artifacts in SEM images. Using a smooth step function, e.g. error function, for each shift that is occurring in each of the images, the required artifactual displacement to be used for correcting the images can be determined.

In order to achieve the aim mentioned above, the GDIC formulation is modified for incorporating imaging artifacts (section 2.2). The new formulation is included in a proper procedure for accurately detecting and removing scan line shifts (section 2.4). The methodology is applied to different virtual experiments to assess the effectiveness, accuracy and convergence behavior of the extended GDIC algorithm (section 3). Finally the method is applied to real SEM images for two cases, one with mechanical deformation and one without (section 4).
Figure 1: Example of line shift artifact in the scanning process; (a) An SEM image at high magnification of a dual phase steel specimen and a zoom of a microstructural feature in two consecutive scans reveals the shift in shortening the feature on the right; (b) displacement in the vertical direction found by local DIC exhibiting two clear jumps.
2 Method

2.1 Brief review of conventional GDIC

The algorithm used in GDIC is based on the conservation of gray scale values as:

\[
\begin{align*}
    r(x, a) &= f(x) - g \circ \phi(x, a) = f(x) - g(\phi(x, a)) ; \\
    \phi(x, a) &= x + u(x, a)
\end{align*}
\]  

(1)

where the residual is the difference between gray values in the reference image \( f \), at original position \( x \), and the deformed image \( g \) at deformed position \( \phi(x) \). The mapping function \( \phi \) implicitly defines the displacement field \( u(x) \). Notational convention of Neggers et al. (2016) are used, where the operator \( \circ \) shows the composition of two functions.

The mapping function is defined by a set of degrees of freedom (dofs) stored in the column matrix \( a = [a_1, a_2, \ldots, a_n]^T \). Due to noise in the images and the inaccuracy of the regularization used in \( \phi(x, a) \), the grey scale conservation leads to a non-zero residual field. This residual field is minimized with respect to \( a \) using a least squares approach. As explained in detail in Neggers et al. (2016), this results in a nonlinear system of equations which is linearized to yield an iterative Newton-Raphson scheme for updating the dofs, \( \delta a \) at each iteration:

\[
M \delta a = b
\]  

(2)

Each element of \( M \) and \( b \) in equation (2) are defined as:

\[
M_{ij} = \int_{\Omega} L_i(x)L_j(x)dx
\]  

(3)

\[
b_i = \int_{\Omega} r(x, a)L_i(x)dx
\]  

(4)
where \( i, j = 1, 2, \ldots, n \) (with \( n \) the number of degrees of freedom) and \( \Omega \) is the domain over which the problem is solved i.e. the region of interest in the images. Note that the matrix \( M \) results from the Hessian matrix of a full-Newton method after neglecting two higher order terms, see Neggers et al. (2016). The matrix \( L_i \), in equations (3) and (4) reads:

\[
L_i(x) = \nabla (g \circ \phi(x)) \frac{\partial \phi(x, a)}{\partial a_i}
\]  

\( L_i \) is made of the inner product of \( \nabla (g \circ \phi(x)) \), the gradient of the deformed image assessed at position \( \phi(x) \), and \( \frac{\partial \phi(x, a)}{\partial a_i} \), the sensitivity functions for each degree of freedom. The image gradient can be computed in different ways, affecting the resulting convergence behavior. Neggers et al. (2016) investigated the choice of the image gradient thoroughly. If the mapping function is linearly dependent on the degrees of freedom, the sensitivity functions can be taken as basis functions of the displacement field. This is often the case, though not always.

### 2.2 New GDIC formulation for imaging artifacts

As discussed in the introduction, if SEM images are used for DIC or any other quantitative measurement, the imaging artifacts should be corrected for, to avoid significant errors in the results. Global DIC can be used to eliminate SEM imaging artifacts in a systematic way. However, note that the imaging artifacts may be present in both the reference image \( f \) and the deformed one, \( g \). Figure 2(a) shows the sequential mechanical and artifactual mappings, where \( F \) is the reference pattern free of artifacts, \( G \) is the true deformed pattern (also free of artifacts) and \( f \) and \( g \) are undeformed and deformed images, respectively.
Figure 2(b) depicts the true, artifact-free reference pattern and the position vector of a specific material point, $x$. In order to identify the corresponding gray scale value in image $f$, the position vector has to be corrected through the mapping function $\phi_f(x)$ representing the artifacts in the reference image. The mapping function $\phi_f(x)$ represents the position where the electron beam landed on the specimen’s surface instead of $x$ while scanning image $f$. This is illustrated in Figure 2(c). The same material point in $x$ is mapped into a new true position by the deformation map $\phi_m(x) = x + u(x)$. The deformed pattern $G$ thus obtained is subsequently imaged, and thus also possibly affected by artifacts, which are characterized by $\phi_g(x)$. The composition of these two mapping functions in image $g$ incorporates both the mechanical deformation and the correction needed for the imaging artifacts. The extended residual in gray scale conservation now reads:

$$r(x) = f(\phi_f(x, a)) - g(\phi_g(\phi_m(x, a)))$$ (6)

$$= f \circ \phi_f(x, a) - g \circ \phi_g \circ \phi_m(x, a)$$

Note that in here, $a$ represents the dofs of all the mapping functions as a vector.

Evidently, each mapping function depends only on the degrees of freedom associated with it. However to avoid confusing notations, the complete vector of dofs, i.e. $a$, is used everywhere. Starting from this extended definition of the residual field (6), the solution procedure can be established, providing the same equations (2), (3) and (4), yet with a different definition for $L_i(x)$:

$$L_i(x) = -L_i^f(x) + L_i^g(x) + L_i^m(x)$$ (7)
Figure 2: Non linear mapping functions of artifacts and mechanical deformation in both reference and deformed images: (a) Order in which the mapping functions apply, (b) reference (true) specimen’s pattern $F$, (c) mapped position for $x$ in image $f$ including artifact distortions, and (d) mapped position for the displaced $x$ in image $g$ based on mechanical deformation and artifact distortions.
where $L^f_i(x)$, $L^g_i(x)$ and $L^m_i(x)$ are defined as:

\[
L^f_i = (\nabla f \circ \phi_f) \cdot \frac{\partial \phi_f}{\partial a_i} \quad (8)
\]

\[
L^g_i = (\nabla g \circ \phi_g \circ \phi_m) \cdot \left(\frac{\partial \phi_g \circ \phi_m}{\partial a_i} \circ \phi_m\right) \quad (9)
\]

\[
L^m_i = (\nabla g \circ \phi_g \circ \phi_m) \cdot (\nabla \phi_g \circ \phi_m) \cdot \frac{\partial \phi_m}{\partial a_i} \quad (10)
\]

The present paper focuses on the scan line shift artifacts. This requires a proper
definition of the artifact mapping functions, capturing the scan line shifts mathematically.

Note that the proposed framework can also be used to incorporate two other types of
SEM imaging artifacts, i.e. drift and spatial distortion, if proper sensitivity functions are
included in the artifact mapping functions. This enables to determine the mechanical
deformation field corrected for any artifacts. By focusing on the scan line shift artifacts
only, the influence of drift and spatial distortion is not eliminated, revealing how to
exclusively detect a shift artifact. When the shifts are detected properly, the procedure
introduced in the work by Sutton et al. (2007a) can be used to correct for drift and spatial
distortion. Note that in here the drift and distortion are not captured in an absolute sense,
since it is sufficient to only capture the difference between the two images.

### 2.3 The new GDIC formulation for the scan line shift artifact

In order to define a proper mapping function to describe the scan line shift artifacts, the
underlying cause of the artifact and the trace it leaves in the images should be better
understood. Figure 3 illustrates the mispositioning of the electron beam and the cor-
responding image resulting from it. On the left side of figure 3(a) the horizontal lines
Figure 3: Gradual mispositioning of scanned points (left) and its effect on the registered image (right), resulting in artifactual localized (a) tension and (b) compression. On the pattern, the grey lines are presumed scanning lines while the dots are the actual scanned positions. In the image, the dots define the pixels. The blue color represents no positioning error while the gradual change to brown alignes with the gradual change of the error to it’s maximum (one pixel in this case). The curves, on the other hand, show the gradual change of the mispositioning as reflected in the image.
represent the scanning lines if no positioning error would occur. The circles represent the actual positions where the intensities of pixels are registered. In this sketch, a gradual increase of misposition from zero to one pixel occurs in four scan lines. In the image on the right however, the measured intensity is attributed to the presumed pixel position. This results in an artificial localized stretching of the pattern in the image. A localized compression results in the opposite case, in which the actual scan lines have a larger spacing than the presumed ones, as depicted in figure 3. In fact, in real SEM images the shift is not necessarily occurring just between two scan lines, but it can have a width of a few scan line spacings. The same mispositioning depicted in figure 3 can also occur in the scanning direction (x direction), leading an artificial shear distortion in the images.

Based on the description above, the scan line shifts are efficiently described, by mapping functions based on the error function, as:

$$\phi_f(x) = x + \frac{1}{2}(A_xe_x + A_ye_y) \left(1 + erf\left(\frac{3\sqrt{2}(y - y_0)}{w}\right)\right)$$

(11)

where:

$$erf(z) = \frac{1}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

(12)

The degrees of freedom are $A_x$, $A_y$, $y_0$ and $w$, i.e. the amplitudes in x and y direction, the position and the width of the scan line shift, respectively. Here subscript $f$ indicates that the mapping function belongs to the artifacts present in the reference image, while $g$ for subscript would mean the mapping for artifacts in the deformed image. Figure 4 shows the graphical representation of this mapping function in 1D.
Figure 4: 1D representation of the error function as the mapping function for the scan line shift artifact, defined by four degrees of freedom, i.e. $A_x$, $A_y$ (for the 2D case), $x_0$ and $w$.

### 2.4 Detection and correction of the scan line shifts

In order to solve the nonlinear least squares problem in global DIC, it is common to use a Newton-Raphson scheme, whereby the robustness depends on the initial guess of the degrees of freedom. This initial guess is particularly important for the position of the shift due to the small support of the corresponding sensitivity function. In this section the procedure to detect the presence of shifts in images and the subsequent steps to extract the degrees of freedom accurately are discussed.

To detect possible scan line shifts in the images, a pre-correlation between two images is performed, using only a set of linear polynomials. The pre-correlation obviously neglects the existence of a scan line shift if present, which is therefore reflected in the residual field of the correlation. The resulting degrees of freedom defining the deformation field allow
the polynomial to match the displacements on both sides of the shift in an average sense. This results in a strong gradient in the residual in the direction perpendicular to the scan lines. This pronounced spatial variation in the residual field of a single correlation indicates how many shifts are present in the correlated pair of images. Moreover, it provides a good initial guess of the position of each shift, even though it cannot reveal to which image each scan line shift belongs.

In order to be able to allocate each scan line shift to its corresponding image, the pre-correlation should be performed between all possible pairs of a set of at least three images. This means three separate pre-correlations on three images of the same area of the specimen. Figure 5 shows the row average of the residual fields for three pre-correlations between images 1-2, 2-3 and 1-3, in blue, orange and green, respectively. The horizontal axis is the y-coordinate of each row, along the direction perpendicular to the scan lines. A high gradient in the residual field that occurs in the same position in two pre-correlations represents a scan line shift that exists in the image that is present in both pre-correlations. Thus by comparing the average residual of three pre-correlations all scan line shifts in the images can be allocated to their corresponding images.

When the shift positions are approximated for each image through the pre-correlations, the artifact mapping functions, i.e. \( \phi_f \) and \( \phi_g \), can be assigned for the final correlation between two images. The resulting initial guess for the position is accurate in the range of \( \pm 10 \) pixels. It will be shown in the next section that this accuracy is sufficient to guarantee convergence. The correlation is next performed in two steps. In the first step, the width is fixed to a large value (e.g. 20 pixels) for each shift and only the amplitudes in \( x \) and \( y \)
Figure 5: Row average of the residual fields of 3 pre-correlations between three typical SEM images (1, 2 and 3) providing the initial guess for the vertical position of the shifts. Direction and the position of the shifts are taken as degrees of freedom. The second step is carried out with all four degrees of freedom, using the results of the previous step as initial guesses. Fixing a large width in the first step causes the support of the sensitivity map related to the position degree of freedom to be large. This relaxes the dependence on the line shift position’s initial guess and thus improves robustness. This point will be discussed in more detail in the following section.

Note that all sensitivity functions corresponding to the scan line shift depend on the degrees of freedom, which is due to the nonlinear relation between the mapping function and the degrees of freedom, as in equation (11) and (12). This necessitates updating the sensitivity maps and the corresponding part of the $M$ matrix in each iteration.
3 Validation of the method

The effectiveness and the accuracy of the method explained in the previous section is next assessed through virtual experiments. A number of speckle pattern images are created, on which known distortions associated with the scan line shift artifact are applied. The resulting displacement fields are computed from the images using the GDIC approach presented in the previous section. The error in the correlated displacement field is obtained by comparing the computed field with the exact field used in the generation of the deformed/distorted images. The generation of these images may not introduce any errors in the virtual displacement field in the images, which would induce an uncorrelated contribution in the GDIC method. One of the most common sources of error is the error related to the gray scale interpolation, i.e. bias error (Sutton et al., 2009). The bias error is inevitable in the correlation process. When generating virtual images the same interpolation errors may occur. For this reason discrete interpolation is avoided in the generation process by defining the images as continuous mathematical functions. This function was based on a random distribution of a number of circular Gaussian peaks:

\[ F(x, y) = \sum_i a e^{-\frac{1}{2} \left( \frac{(x-\mu_{ix})^2}{\sigma_x^2} + \frac{(y-\mu_{iy})^2}{\sigma_y^2} \right)} \]  

(13)

where \( a \) is the amplitude of each peak, \( \mu_x \) and \( \mu_y \) are the coordinates of each peak (chosen randomly), and \( \sigma_x \) and \( \sigma_y \) are standard deviations in \( x \) and \( y \) direction respectively. The standard deviations, taken equal here, define the width of each peak (speckle pattern). The image is made with two layers of Gaussian peaks corresponding to two different speckle sizes. The virtual pattern, \( F \) represents the physical pattern on the specimen in a
real experiment. Both images $f$ and $g$ are generated from $F$. In the virtual experiments, the reference image $f$ is considered free of artifacts and is therefore exactly equal to the rasterized version of $F$, with the addition of Gaussian noise only. The deformed image $g$, is generated by mapping the pattern $F$ based on $\psi$, the generation mapping function. The generation mapping function is the inverse of the mapping function that describes the deformation/distortion field that will eventually be present in image $g$, i.e. $\psi(x) = (\phi_g \circ \phi_m(x))^{-1}$. Where $\phi_g$ is defined as in equation (11). Figure 6 shows one of the resulting virtual images with the effect of a smooth scan line shift on a feature in the pattern. Gaussian noise with a standard deviation of either 0.5, 1 or 2.5% of the dynamic range has been added to each image.

The virtual experiments are performed in two stages: first, with a scan line shift only, and next, a scan line shift along with a set of complex deformation/distortion fields representing the mechanical deformation and possible other imaging artifacts.

### 3.1 Virtual experiment with a scan line shift only

A pair of virtual images is generated, one without any deformation and one with a single smooth scan line shift embedded inside. The shift is placed at position $y = 3$ pixels (origin of the coordinate system being at the center of the image) and has a width of 4 pixels with amplitudes of 1 and 2 pixels in $x$ and $y$ direction, respectively. The virtual images are then correlated using the approach proposed in section 2. In order to assess the influence of the initial guess, a series of correlations are performed with the same set of images, but with a different initial guess for the degrees of freedom of the shift. Figure 7 plots
Figure 6: Typical virtual image created by superposition of Gaussian functions and the zoomed feature showing the effect of a smooth scan line shift incorporated in the deformed image.

The average convergence success against random perturbations of a certain amplitude in the initial guess with respect to the exact values. Each point in the plot represents ten correlations for a certain perturbation in the initial guess of the degrees of freedom. A value of one for the average convergence success means that all the ten correlations with that specific perturbation amplitude have converged, while zero means that none have converged. The convergence criteria is based on the mean of the absolute value of change in the degrees of freedom, for which a tolerance of $1e^{-5}$ is adopted. The only difference between the different curves shown is the noise level added to the images. The standard deviation of the maximum level of noise implemented in the virtual images here equals 2.5% of the dynamic range. One noise level is also shown for a direct (1 step) correlation.
Figure 7: Average convergence success versus amplitude of the perturbation applied to the initial guess for different values of noise in virtual experiments. 1-step correlation involves all four degrees of freedom in a single correlation (direct correlation for amplitudes, position and the width of shifts), whereas 2-step correlation corresponds to a pre-correlation of only amplitudes and position while keeping the width constant, followed by a second correlation of all dofs.
Figure 8: Iterative error evolution for virtual images containing a scan line shift only, without noise and with 10 pixels of perturbation in initial guess (iteration 1 to 10; first step, iteration 11 to 15: second step) of all four dofs, in contrast to the 2 step correlation procedure described in the previous section. The large influence of initial guess on the 1 step correlation compared to the 2 step correlation, justifies the use of the latter. In case of 0.5% and 1% of noise, the convergence success is 1 up to more than 90 pixels of perturbation in the initial guess. This value equals 80 pixels for a noise level of 2.5%.

Figure 8 shows the error in all degrees of freedom of the scan line shift (amplitude in x and y direction, position and width) for each iteration and for both steps of the correlation. The error for the width is meaningful only for the second step, where it is used as a degree of freedom; therefore it is plotted only for the iterations related to the second step. The
final error is negligibly small (4.8e−4 pixel) for both amplitudes and relatively small
(3.1e−1 pixel) for both position and width at final convergence. The higher value of error
associated with the position and the width, compared to the amplitudes, is due to the
fact that sub-pixel error in the evaluation of position and width influences the residual
field only in the width of the scan line shift. In other words, a small error in degrees of
freedom related to position and width of a line shift causes an increase in only a small
area of the residual, while the same relative error in the amplitude of the line shift affects
a big area of the residual. This results in the observed lower sensitivity to the width and
position dofs.

3.2 Virtual experiment with a complex deformation field

A second series of image pairs is created, with a localized mechanical deformation field
alongside the scan line shift as well as drift and spatial distortion was incorporated in the
deformed image. Figure 9 depicts the superposition of all deformation and distortion fields
in x and y directions. The bi-sinusoidal displacement field in x direction characterizes
kinematic localization in the mechanical deformation field. The error function (11) is
implemented to represent the line shift artifact. The drift artifact is taken as simple shear
in y direction. The spatial distortion is chosen as $U_d(\rho) = k_d \rho^3$, which resembles the
radial distortion of an optical lens (Lava et al., 2013) with $\rho$ is the radial distance from
the center of the image.

The virtual images are correlated with the proposed approach. The artifact mapping
function is regularized with the sensitivity functions for the line shifts, whereas the me-
Figure 9: Total displacement fields used in the virtual image of section 3.2, (a) in $x$ direction, (b) in $y$ direction. The deformation field consists of: (1) a bi-cosine distribution of displacement in $x$ direction representing a localized mechanical deformation field; (2) a simple shear in $y$ direction representing drift; (3) a $3^{rd}$ order radial displacement field representing spatial distortion artifact; (4) a single line shift, defined through the error function (12).
Figure 10: Iterative error evolution for virtual images with a complex deformation field and without noise. The initial guess for the scan line shift dofs is perturbed by 10 pixels with respect to their exact values; 15 $\times$ 15 bilinear quadrilateral finite elements are used to regularize the mechanical mapping function; the line shift sensitivity functions are used for the artifacts mapping (showing the iterations of only the second, i.e. final step of the correlation)
mechanical mapping function is regularized by a set of FEM (imposing no global kinematic constrains other than continuity) basis functions in order to capture the combination of drift, spatial distortion and the localized mechanical deformation. Note that the intention of capturing these fields jointly is only to guarantee a proper detection of the shift. The error in the parameters of the line shift are plotted against the iteration numbers of the final step of the correlation in Figure 10 for a case of $15 \times 15$ bilinear quadrilateral elements. The error for the amplitudes is again negligibly small ($1.2e-2$ pixel), whereas for the position and width the errors are small and in the sub-pixel range ($3.2e-1$ pixel). This demonstrates the reliability of the method, even in the presence of a complex mechanical deformation field and other distortion fields. Even if these complex fields are unknown, it is sufficient to capture them to a reasonable degree (the subpixel accuracy of DIC) to guarantee proper extraction of the line shift artifact.

Figure 11 shows errors in shift parameters for different discretization of the FEM basis functions, i.e. $4 \times 4$, $6 \times 6$, $8 \times 8$, $12 \times 12$, $16 \times 16$, $24 \times 24$ and $32 \times 32$ bilinear quadrilateral elements. If the number of elements is high enough to accurately capture the underlying displacement fields, the extraction of the parameters of the scan line shift turns out to be even more accurate. A plateau in the errors is observed for a discretization of $16 \times 16$, which is most pronounced for the amplitudes.

4 Application to real SEM images

The method for detecting and removing scan line shift artifacts is next applied to real SEM images. In this section, the study is again divided in two parts. First, the case
Figure 11: Final error for different discretizations of the displacement field to capture the total effect of the drift, spatial distortion and mechanical deformation in the virtual experiment.
Figure 12: SEM images of (a) a dual phase steel specimen, and (b) a bainitic steel specimen, taken in a FEI Quanta 600F microscope in secondary electron mode.

without any mechanical deformation is discussed, followed by a second case using SEM images taken during an \textit{in-situ} tensile test inside an SEM chamber exhibiting mechanical deformation between subsequent images.

4.1 SEM images with no mechanical deformation

A set of three SEM images were taken of a dual phase (DP) steel specimen in an FEI Quanta 600F microscope in secondary electron imaging mode. The images were taken one after another without any deformation or translation of the specimen. The field of view of the captured images is about $30 \times 30 \mu m$, see figure 12(a). The natural pattern present in the images results from chemical surface etching, resulting in a surface topology that uncovers the microstructure of the material.

A local digital image correlation (LDIC) between pairs of images is performed using...
the commercial LDIC package MatchID. A subset size of 41 pixels and a step size of 6 pixels is used for this correlation. Figure 13(a) shows the vertical displacement map from the LDIC. Two distinct scan line shifts can be observed, with roughly half a pixel amplitudes (in \(y\) direction), one in positive, and the other in negative direction.

Next, these two images are used to correct for the observed scan line shifts using the proposed method. Firstly, a series of pre-correlations (using only first order polynomial and no enrichment for the scan line shifts) between all three images is performed to retrieve a reasonable initial guess for the position of the shifts and also to allocate each shift to its corresponding image. After the coarse detection of the shifts, the mapping functions of artifacts in \(f\) and \(g\), i.e. \(\phi_f\) and \(\phi_g\) respectively, are assigned. A set of FEM basis functions consisting of \(15 \times 15\) bilinear quadrilateral elements defines the mechanical deformation mapping function, \(\phi_m\). Since there is no mechanical deformation in this case, this mapping function only captures the difference in drift and spatial distortion artifacts possibly present in the images, enabling a precise detection of the scan line shift artifacts. The correlation is performed and both images are corrected for the scan line shifts, thereby effectively eliminating the shifts from the images. To assess the effectiveness of this methodology, LDIC, with identical settings as used for the uncorrected images, is performed on the corrected images. The map of the displacement in \(y\) direction is depicted in Figure 13(b). The two shifts are completely eliminated from the displacement fields. Figure 14 shows the average row values of \(U_x\) and \(U_y\) as a function of the vertical position of the row for the local DIC results before and after elimination of the shifts. In figure 14(b), both scan line shifts, of 0.55 and \(-0.49\) pixels in \(y\) direction respectively,
Figure 13: Vertical displacement in a DP steel specimen before and after shift artifact elimination. Both displacement fields are determined by LDIC.

are eliminated completely, i.e. there is no trace left of an increase or decrease of $U_y$ after elimination. The $x$ component of the shifts are eliminated with the same accuracy, as evidenced in figure 14(a).

4.2 SEM images of *in-situ* tensile test

A set of three SEM images is taken of a bainitic steel specimen during an *in-situ* tensile test in an FEI Quanta 600F microscope in secondary electron imaging mode. The images are from three subsequent deformed states of the specimen subjected to tension in the vertical, $y$ direction. The field of view of the captured images is close to $25 \times 25 \mu m$, see figure 12(b). The natural pattern in the image again results from chemical surface etching, resulting in a surface topology disclosing the microstructure of the material.

LDIC between the two images is again performed using MatchID. The same settings used before (subset size of 41 pixels, step size of 6 pixels) are adopted for this correlation.
Figure 14: Average row values of displacement in (a) $x$ and (b) $y$ direction as a function of the vertical position of the row, found by LDIC on SEM images of a DP steel specimen, before and after elimination of scan line shift artifacts.
Figure 15(a) shows the vertical displacement map resulting from LDIC. A distinct jump is visible of a magnitude close to 5 pixels spanning a large width. Note that this is one of the extreme cases of a scan line shift artifact observed with this electron microscope in terms of amplitude and width, making it a valid test case for shift artifact elimination.

The proposed procedure is applied to the three images. Since there is only a single shift corresponding to image $g$, the artifacts mapping function of the reference image, $\phi_j$, can be ignored. One shift is allocated to $\phi_g$ with the proper initial guess, obtained from the pre-correlations. A set of FEM basis functions made of $15 \times 15$ bilinear quadrilateral elements defines $\phi_m$. In this case, the mechanical mapping function represents the mechanical deformation in addition to drift and spatial distortion artifacts affecting images. Again, the purpose is to secure a proper detection of the scan line shift artifact. The image $g$ is next corrected for the scan line shift and local DIC is performed on the corrected image with respect to the same reference image. The corresponding vertical displacement map of this correlation is depicted in figure 15(b). A proper elimination of the scan line shift artifact is observed, despite the presence of a strong artifact and mechanical deformations. Note also that the shift is located close to the top edge of the image, which poses no problem for the methodology neither. Figure 16 reveals the row average of $U_x$ and $U_y$ for the LDIC results, before and after elimination of the scan line shift. The shift of 4.9 pixels amplitude in $y$ direction is properly eliminated. The ratio of the amplitude of the residue of the sudden change in the displacement after elimination, to that of before elimination is 0.002. The elimination of the shift in the $x$ direction is performed with the same level of precision, as presented in figure 16(a).
Figure 15: Vertical displacement in a Bainitic steel specimen before (a) and after (b) elimination of the occurring shift artifact (displacements assessed by LDIC).

5 Conclusions

Images taken by scanning electron microscopy exhibit artifacts that may result in considerable errors if used for determining mechanical deformation fluctuation fields by DIC. These artifacts can be divided into three categories: spatial distortions, drift and scan line shifts. This paper proposes a robust method to deal with scan line shifts, using a systematic approach that does not rely on averaging of images. The nonlinear composition of the effect of mechanical deformation and the distortions caused by the artifacts is taken into account, leading to an extended global DIC framework suitable for dealing with artifacts. A regularization enrichment based on error functions is proposed to identify scan line shift artifacts and to eliminate them from the affected images.

The method is assessed with a series of virtual experiments based on artificially generated and deformed patterns. The influence of the initial guess of the shift parameters
Figure 16: Row average of displacements in (a) $x$ and (b) $y$ direction, obtained by LDIC on SEM images of Bainitic steel specimen, before and after removal of scan line shift artifacts.
on the robustness and convergence is tested, enabling convergence even with an initial
guess error of 80 pixels for the considered virtual test cases. The resulting amplitude of
the shifts present an error in the order of $10^{-4}$ and $10^{-2}$ pixels, without or with other
deformation fields respectively. The position and the width of the shifts are evaluated
with sub-pixel accuracy in all virtual experiments.

The proposed methodology is applied on two physical sets of real SEM images, one
without mechanical deformation and the other taken from a uni-axial tensile test. The
images taken revealed scan line shift artifacts up to 5 pixels amplitude. In both cases, all
shifts are eliminated accurately. The LDIC maps of the images before and after removal
of the shifts emphasize the need for the proposed elimination method and pinpoint the
efficiency of the method. The proposed method relies on minimal data acquisition for
artifact detection and removal. The adopted deterministic regularization for this type of
artifact results in a high robustness, applied to extreme cases of line shift artifacts (high
amplitude of shifts). The newly proposed extended GDIC general framework based on
nonlinear mapping functions for the artifacts can be extended to deal with other types
of artifact as well, e.g. drift and spatial distortion, which will be discussed in future
publications.

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