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Closed-Loop Autofocus Scheme for Scanning Electron Microscope

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Abstract. In this paper, we present a full scale autofocus approach for scanning electron microscope (SEM). The optimal focus (in-focus) position of the microscope is achieved by maximizing the image sharpness using a vision-based closed-loop control scheme. An iterative optimization algorithm has been designed using the sharpness score derived from image gradient information. The proposed method has been implemented and validated using a tungsten gun SEM at various experimental conditions like varying raster scan speed, magnification at real-time. We demonstrate that the proposed autofocus technique is accurate, robust and fast.

1 Introduction

For high accuracy during manipulation tasks or micro-nanoscale measurements under a scanning electron microscope (SEM), high quality and sharp images are always required. For this purpose, an efficient and reliable SEM autofocus algorithm has to be executed before the manipulation process. In general terms, autofocus is a process of maximizing the image sharpness by regulating the device focus sets. There are two types of autofocus techniques: active methods, using a different subsystem to modify the lens position and passive methods, which solely rely on the image sharpness information. Out of the two, passive methods are commonly employed for microscopic devices. Since the geometry and projection model of a SEM are different to optical systems \cite{1, 2}, the autofocus process is different. Most of the autofocus methods are based on evaluating the image sharpness score i.e., the score should reach a single optimum of a selected sharpness function at the in-focus image. For this purpose, many sharpness criteria such as image variance, autocorrelation, wavelets, Fourier transform were discussed for microscopic applications \cite{3}. A comparison of these criteria regarding electron microscopy was discussed in \cite{4}.

To perform passive autofocus process with SEM, a former method is to obtain a sequence of images within a defocus range and to compute their sharpness scores. The optimal SEM focal length that corresponds to the maximum of sharpness score is then obtained \cite{5}. The main drawback in this approach is that it requires the acquisition of many images, which is practically time consuming due to the high focus range of SEM. Alternatively, a later method is to start with an initial set of SEM imaging parameters that correspond to a defocus image. Then an iterative algorithm is used to search for the best focus position \cite{6, 7}. Even though these methods are effective, they are highly dependent on the search history. Rudnaya \cite{8} has proposed to use Nelder–Mead method for searching the optimum of image variance. An alternative method has been proposed in \cite{9}, based on fitting the sharpness function to a quadratic polynomial approximatively using some initial measurements. In \cite{10}, the autofocus has been achieved by computing the derivative of sharpness function numerically. Finally, statistical learning-based autofocus methods were studied for SEM \cite{11}, but were never implemented in real-time.

In this paper, we consider the autofocus issue as a control problem and propose a direct closed-loop control scheme to solve it. The objective is to control the device focal length (working distance) iteratively based on the time variation of the gradient information of acquired image. An analytical formulation of the relation between the displacement of the working distance and the variation of the gradient information is proposed. The considered method advances the available methods in different ways. First, it overcomes the problem of hysteresis since it is independent of the search history and directly reaches the optimal focus position. Next, the method automatically circumvents unnecessary defocus positions that makes it faster than the search-based techniques. Finally,
2 Background on SEM Focusing

2.1 SEM Focusing Geometry

In general, the SEM images are formed by scanning a sample surface by means of a focused beam of high energy electrons. Different sets of electromagnetic lenses in the SEM electron column are responsible for performing the focusing task. The first are the condenser lenses that control the beam diameter and the second are the objective lenses that focus the spot sized beam on to the sample surface. Apart from them, an objective aperture is present in between them to filter out the non-directional electrons. The distance measured electronically between the final pole piece of the objective lens and the focal plane is the electronic working distance. The distance measured between the final pole piece of the objective lens and the working distance which plays a vital role in the focusing process. This distance depends on two factors: the beam acceleration voltage and the current passing through the objective lens. In this work, we assume the former remains constant and the main focusing is performed only using the latter. The total focusing process is illustrated in the Fig. 1(a). For any selected magnification, at a distance \( D \) on both sides of the focal plane, the beam diameter is two times pixel diameter. This results in the images that look to be acceptably in-focus.

2.2 SEM Image Formation

The general image formation model, which is commonly used in the case of optical microscopes [12], can be extended to use with a SEM [11]. Considering an extremely small area element \( dxdy \) centered on \((x, y)\), the secondary electron (SE) current emitted from this area is

\[
ds(x, y) = \delta(x, y)\varphi(x, y)dxdy,
\]

where \( \varphi(x, y) \) is the incident current density at the point \((x, y)\), \( \delta(x, y) \) is a yield coefficient which is as-

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use image gradient is that it shows a good compromise in the case of unstable image contrast, which has to be considered with SEM [14]. Besides, in [15] it has been proposed to use image gradient information to perform vision-based positioning tasks and a similar process could be envisioned for an autofocus task. However, due to the parallel projection model at high magnification which is inherent to a SEM [2], the perspective projection-based control law proposed in [15] cannot be employed for the SEM. To tackle this problem, we propose in this section a direct projection model-free approach to derive the control law for full scale autofocus.

Considering the fact that the image gradient varies when the image focus changes i.e., when the working distance varies, we aim to update the working distance by a closed-loop control law to obtain the maximum of image gradient. For an acquired image \( i(x, y) \), the squared norm of the gradient \( g(x, y) \) at a point \( (x, y) \) is expressed by

\[
g(x, y) = \| \nabla i(x, y) \|^2 = \nabla^2_x i^2(x, y) + \nabla^2_y i^2(x, y)
\]  

where, \( \nabla^2_x i^2(x, y) \) and \( \nabla^2_y i^2(x, y) \) represent the squares of gradient in \( x \) and \( y \) directions, respectively. Considering the squared norm of the gradient \( G \) for a whole image \((M \times N)\) as the sharpness function to be maximized by varying \( W \), we have

\[
\hat{W} = \arg \max_W G(W)
\]  

where

\[
G(W) = \sum_{x=0}^{M} \sum_{y=0}^{N} g(x, y, W)
= \sum_{x=0}^{M} \sum_{y=0}^{N} (\nabla^2_x i^2(x, y, W) + \nabla^2_y i^2(x, y, W)).
\]  

Here instead of extracting any local features, a global feature \( G \) is defined over a whole image. Fig. 3 shows the variation of image gradient \( G \) for a series of SEM electronic working distances. In fact, it is not necessary to take into account any local information (i.e., shape, texture and uniformity of the sample), since the image gradient for most of the pixels increases (or decreases) when changing working distance, resulting a smooth sharpness function which has one evident optimum (at the desired working distance). Considering the autofocus task as a closed-loop control law, the objective is to compute the variations of the working distance \( \dot{W} \) from the variation of \( G \) for achieving an optimal SEM focus set.

In order to employ image gradient information as the sharpness function for full scale in a SEM, the relation between the temporal variations of working distance \( \dot{W} \) and image gradient \( G \) is considered:

\[
\dot{G} = G \dot{W}.
\]

The Jacobian \( J_G \) that links the variations of working distance \( W \) and image gradient \( G \) in (8) can be expressed by

\[
J_G = \frac{\partial G}{\partial \sigma} \frac{\partial \sigma}{\partial W}
\]  

where, \( \sigma \) is the standard deviation of Gaussian kernel given in (4). For a small displacement of \( W \), considering a proportional relation between \( \sigma \) and \( W \),

\[
\frac{\partial \sigma}{\partial W} = k,
\]

leading to

\[
J_G = \frac{\partial G}{\partial W} = k \frac{\partial G}{\partial \sigma}
\]  

From (7), \( \frac{\partial G}{\partial \sigma} \) can be expressed as

\[
\frac{\partial G}{\partial \sigma} = \sum_{x=0}^{M} \sum_{y=0}^{N} 2(\nabla^2_x i(x, y) \frac{\partial \nabla^2_x i(x, y)}{\partial \sigma} + \nabla^2_y i(x, y) \frac{\partial \nabla^2_y i(x, y)}{\partial \sigma}).
\]

Next, (3) can be rewritten as follows:

\[
i(x, y) = \sum_{m} \sum_{n} i^2(x - m, y - n)h(m, n).
\]

From (4), we get the derivative of the Gaussian kernel:

\[
\frac{\partial h(m, n)}{\partial \sigma} = \frac{1}{2\pi} (m^2 + n^2 - 2\sigma^2) e^{-\frac{m^2 + n^2}{2\sigma^2}}
\]

Considering (12) and (13), we have

\[
\frac{\partial \nabla^2_x i(x, y)}{\partial \sigma} = \sum_{m} \sum_{n} \nabla(i^2_x(x - m, y - n)) \cdot \frac{1}{2\pi} (m^2 + n^2 - 2\sigma^2) e^{-\frac{m^2 + n^2}{2\sigma^2}}
\]

and

\[
\frac{\partial \nabla^2_y i(x, y)}{\partial \sigma} = \sum_{m} \sum_{n} \nabla(i^2_y(x - m, y - n)) \cdot \frac{1}{2\pi} (m^2 + n^2 - 2\sigma^2) e^{-\frac{m^2 + n^2}{2\sigma^2}}
\]

Replacing (14) and (15) in (11), we can finally compute \( J_G \), which is used to derive the control law.

---

**Figure 3.** Evolution of image gradient with respect to working distance.
3.2 Control Law

The objective of our approach is to maximize the gain \( G \) by controlling the working distance \( W \) to obtain an optimized focus of SEM. In order to maximize \( G \), we are going to minimize a cost function given by

\[
\varepsilon(W) = \alpha e^{-\beta G(W)} - \gamma
\]

where, \( \alpha, \beta \in \mathbb{R}^+ \) are adaptive gains that control the variation of working distance and the speed of convergence. \( \gamma \) is a small positive value that can be considered as a threshold to determine if the optimal focus is reached. The algorithm will stop when \( \alpha e^{-\beta G(W)} \leq \gamma \). Considering an exponential decrease of the error i.e., \( \varepsilon = -\lambda \varepsilon \), the control law is:

\[
\xi = -\lambda J_\varepsilon^{-1} \varepsilon
\]

where, \( \xi \) is the velocity along the focal axis and \( J_\varepsilon \) is the Jacobian and can be expressed by

\[
J_\varepsilon = \frac{\partial \varepsilon}{\partial W} = -(\varepsilon + \gamma) \beta J_G.
\]

Rewriting (17) using (18), leads to

\[
\xi = \frac{\lambda e}{(\varepsilon + \gamma) \beta J_G}
\]

Subsequently, the \( W \) displacement (working distance) to be set with the SEM has been computed as follows

\[
\Delta W = \xi \Delta t
\]

where, \( \Delta t \) is the time taken between the two acquired images. For each iteration, the working distance is updated as given by

\[
W_{\text{new}} = \begin{cases} W_{\text{prev}} - |\Delta W| & \text{if } W_0 \text{ close to } W_{\text{max}} \\ W_{\text{prev}} + |\Delta W| & \text{if } W_0 \text{ close to } W_{\text{min}} \end{cases}
\]

where \( W_{\text{new}} \) is the working distance to be updated, \( W_{\text{prev}} \) and \( W_0 \) are previous and initial working distances, respectively, \( |\Delta W| \) is the magnitude of \( \Delta W \), \( W_{\text{max}} = 50 \) and \( W_{\text{min}} = 1 \) are the factory-provided maximum and minimum values for the electronic working distance (in mm) of the employed SEM, respectively. In our experiments, (21) is used to control the direction of displacement computed by the control law. For the initial working distance close to a middle value between 1 and 50, according to the single maximum in the evolution of image gradient with respect to working distance (see Fig. 3), the direction can be obtained by comparing \( G(W_0) \) with \( G(W_0 + dW) \), where \( dW \) is a small change in working distance.

4 Real-time Validations in SEM

4.1 Experimental Set-up

In order to validate the proposed method, different experiments have been realized. Fig. 4 shows the experimental set-up architecture used for this work. The SEM used is a Jeol JSM 820 tungsten gun SEM equipped with a conventional Everhart-Thornley SE detector. Its electron column is equipped with different sets of electromagnetic lenses and an objective aperture strip containing 4 changeable apertures of different diameters. The magnification of the SEM varies from 10 to 100,000 and the maximum allowable electronic working distance is 50 mm. A beam control and image acquisition system, DISS5 (from point electron GmbH) has been interfaced with the microscope. It is mainly responsible for sending the scan parameters to SEM and to acquire the data coming from SE detector. Later this data is amplified, digitized and saved as an image in the computer to which the DISS5 is connected. All the autofocus experiments are performed in this computer using the SEM images of size 512 \times 512 pixels and are monitored using the developed special purpose graphical user interface program. Besides, DISS5 provides a user interface control for the device focus by linking the working distance with a range of focus steps i.e., each step corresponds to a specific working distance. For real experiments with the system, a model given by (22) has been obtained by approximating the curve using least squares fitting. This model will be used to compute the corresponding focus step for a working distance given by (21) to modify the device focus.

\[
F = \begin{cases} \sum_{j=1}^{C=6} p_j W^{C-j} & \text{if } 1 \leq W < 50 \\ 586 & \text{if } W \geq 50 \\ 973 & \text{if } W \leq 1 \end{cases}
\]

where, \( p_{i=1,6} \) are the coefficients of the model and \( F \) is the focus step of the SEM. As the acceleration voltage used to excite the electrons vary the focusing model, for each voltage used in this work, a corresponding model has been derived. However, for the experiments, the voltage is fixed for all the tests performed with a specific sample.

4.2 Validation of the Method

Initial test is performed to validate the performance of the proposed method. The acceleration voltage used...
Focus steps, \( F \)

Velocity, \( \xi \)

Working distance, \( W \)

<table>
<thead>
<tr>
<th>Mag.</th>
<th>Obtained ( W ) (mm)</th>
<th>Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>20.957</td>
<td>20.984</td>
</tr>
<tr>
<td>600</td>
<td>20.830</td>
<td>20.864</td>
</tr>
<tr>
<td>900</td>
<td>21.114</td>
<td>21.037</td>
</tr>
<tr>
<td>1200</td>
<td>20.875</td>
<td>21.017</td>
</tr>
</tbody>
</table>

RMSE: 0.049

Table 2. Autofocus results using high scan speed.

<table>
<thead>
<tr>
<th>Mag.</th>
<th>Obtained ( W ) (mm)</th>
<th>Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>20.891</td>
<td>20.854</td>
</tr>
<tr>
<td>600</td>
<td>20.934</td>
<td>21.028</td>
</tr>
<tr>
<td>900</td>
<td>21.000</td>
<td>21.017</td>
</tr>
<tr>
<td>1200</td>
<td>20.875</td>
<td>20.831</td>
</tr>
</tbody>
</table>

RMSE: 0.055

Figure 5. Microscale calibration rig

Figure 6. Validation of the method at a magnification of \( \times 300 \): Evolution of (a) focus step and image gradient (b) absolute velocity and working distance during the proposed process.

4.4 Discussion

The obtained experimental results show the accuracy and efficiency of the proposed method in the case of various real world scenarios. Since the Jacobian is computed analytically, the autofocus procedure is more robust w.r.t. the alternative methods (i.e., numerical computation of Jacobian or approximating the sharpness function to a simple function). Since the sum of squared norm of gradient has been considered as a global sharpness function to be optimized by a closed loop control law, the efficiency of the method...
Last column depict the in-focus images. will not be affected by changing the sample or the magnification of the SEM.

However, there are few limitations where the performance of the method could be affected. It should be mentioned that in our experiments the sample is flat. If the sample is far from perpendicular to the vision sensor, there is a risk that the sharpness function could feature multiple optimum. Generally in a SEM, the support of sample can be set to be perpendicular to the electron gun by the SEM software. In this case, the tilt is normally smaller than the field of view, keeping the sample in-focus when the autofocus procedure achieve the optimization. Next, similar to the other autofocus techniques (using any imaging device), the proposed method also requires the objects with sufficient texture information.

5 Conclusions

In this paper, an efficient and robust closed-loop control scheme has been proposed for a full scale autofocusing of SEM. The image gradient information is considered as the sharpness score in designing the vision-based control law. The optimum value of focus i.e., the maximum image sharpness has been obtained by updating the device working distance iteratively. The method has been validated on different experimental conditions. Different from other SEM autofocusing techniques, the derivative of the cost function is computed analytically, which makes the algorithm robust. Since the designed cost function reduces exponentially, the proposed method quickly converges to the optimal value.

References