Multi-scale Calibration Board Based Accurate Calibration of a Scanning Electron Microscope

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Abstract. We present a new calibration method based on multi-scale calibration board for scanning electronic microscopy (SEM) at low magnifications. The implementation of the calibration mainly depends on automatic center-point features detection from the calibration board image instead of corner detection. The center-point feature is the centroid of each squares, which is obtained via morphological processing. We use the calibration model consisting of projective model and static distortion model. It is proved the point detection proposed in this paper is more accurate, efficient and robust, compared with corner point detection in the traditional calibration process. Then, reprojection error is used to evaluate the accuracy of the calibration results. At last, the method is efficient and reliable with accuracy, which is testified by experiment.

Keywords: Calibration; Scanning electronic microscopy; Center-point extraction; Perspective model.

1. Introduction

With the exploration and research of human beings in the microscopic field, the scale of research objects gradually developed to the nanometer level. But micron is the resolution limit of optical microscope. So, scanning electronic microscopy (SEM), which has the advantages of high resolution, large depth of field and fast imaging speed, became the commonly used instrument in the micro-vision field. The calibration is a necessary issue to be solved, when it comes to the information of measurement or pose from the acquired images.

Many research scholars have done a lot of related research about calibration in micro-vision system [1-5]. However, most of them involve the field of measurement, mainly related to the calibration of parameters of two-dimensional planes. Novikov and Y. A calibrated the pixel size, electron-beam size and the nonorthogonality of the electron beam from two coordinates with a new test object made of silicon which has pitch structures consisting of grooves and cross-shaped protrusions [6]. The silicon relief structures are used to calibrate the magnification and the working distance of SEM for improving the accuracy of critical measurement [7, 8]. However, it is necessary to calibrate the imaging model of SEM because of the need of depth information in the field of three-dimension reconstruction and micro manipulation. Although, a SEM and an optical microscope differ greatly in terms of structure and principle, the projection model used in classical camera model is also applicable to a scanning electron microscope under low magnification. A. C. Malti proposed a magnification-continuous model of the SEM [9]. L. Cui and Marchand optimized calibration results using a nonlinear minimization process [10].
The above calibration methods are all based on high-precision low-noise images from multi-scale calibration board with squares going from different size. SEM could provide low-noise image at cost of increased time. And by the increases of the tilt angle, part of calibration plate image is blurred. It will greatly reduce the accuracy of corner extraction and thus reduce the accuracy of the calibration results. Therefore, we proposed a calibration method of a SEM based on center-point extraction in this paper. The formulation has strong noise immunity ability. Simultaneously, it is simple and versatile.

2. Theory

2.1. Perspective model

The final purpose of this calibration is to provide some prior information about pose estimation for micro operations and 3D reconstruction in a SEM. Since wide viewing area and electron large beam sweep angle at low magnifications generally ranged from 20x to 500x, perspective model (see Figure 1) can be considered. Such model has clear physical meaning in optical camera, but the electronic coil is similar to an optical lens and the electron beam as light for sake of understanding the physical implication of the model in a SEM.

![Figure 1. Projection model.](image)

As show Figure 1, \( O_c \) refers to projection center. In the visual sensor frame \( F_c \), a point on the calibration pattern can be expressed by \( X_c = (x_c, y_c, z_c, 1)^T \). Similarly, \( m = (x, y, 1)^T \) is the homogeneous coordinates of the point from \( X \) projected on the image plane. Simultaneously the point can be expressed in pixel \( m_p = (u, v) \), \( p = (u_0, v_0) \) is the principal point coordinate.

\[
\begin{align*}
  u &= u_0 + \frac{f}{d_x} x \\
  v &= v_0 + \frac{f}{d_y} y
\end{align*}
\]

(1)

\( f \) refers to focal length, \( d_x \) and \( d_y \) represent pixel/meter ratio respectively in the x, y-axis directions. Thus, it could be obtained the relation between the point \( m_p \) with pixel coordinates in the image plane and the point \( X_c \) on the calibration plate. Suppose \( X_w = (x_w, y_w, z_w, 1)^T \) is the homogeneous coordinates of \( X \) expressed in the world coordinate frame \( F_w \). It can be expressed by

\[
\begin{bmatrix}
  x_c \\
  y_c \\
  z_c \\
  1
\end{bmatrix} =
\begin{bmatrix}
  R_{3\times3} & t_{3\times1} \\
  0_{3\times3} & 1
\end{bmatrix}
\begin{bmatrix}
  x_w \\
  y_w \\
  z_w \\
  1
\end{bmatrix}
\]

(2)

To simplify expression, let \( f_x = f/d_x \), \( f_y = f/d_y \). Finally, according to equations (1) and (2) the perspective model can be written as:

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} =
\begin{bmatrix}
  f_x & 0 & u_0 \\
  0 & f_y & v_0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  R_{3\times3} & t_{3\times1} \\
  0_{3\times3} & 1
\end{bmatrix}
\begin{bmatrix}
  x_w \\
  y_w \\
  z_w \\
  1
\end{bmatrix}
\]

(3)
Where $K$ and $T$ is the matrix of intrinsic and extrinsic of the geometric model respectively. The purpose of the calibration is to estimate the value of $f$, $d_x$, $d_y$, $u_0$, $v_0$ considered as the extrinsic parameters and $R_{3\times3}$, $t_{3\times1}$ are the rotation matrix and translation vector considered as the intrinsic parameters. $T$ clarifies the position of calibration plane in the visual sensor frame or pose information.

2.2. Image distortion model
The distortion model most commonly used in classical models is mainly composed of two part, which include radial distortion and tangential distortion. The relation between the point position $m$ in pixel coordination and $m_p$ in perspective projection in equation (1) expressed by

$$
\begin{align*}
    u &= u_0 + f_x\delta_x(x + p_x) \\
    v &= v_0 + f_y\delta_x(y + p_y)
\end{align*}
$$

(4)

where the radial distortion is approximately expressed by

$$
\begin{align*}
    \delta_x(x, y) &= k_x(x^2 + y^2) \\
    \delta_y(x, y) &= k_y(x^2 + y^2)
\end{align*}
$$

(5)

The tangential distortion can be approximately expressed by

$$
\begin{align*}
    p_x(x, y) &= p_1(3x^2 + y^2) + 2p_2xy \\
    p_y(x, y) &= p_2(3x^2 + y^2) + 2p_1xy
\end{align*}
$$

(6)

2.3. Calibration pattern
Scanning electron microscope observe sample mainly by using secondary electron signal, and the magnification range is very wide. Hence, it is not easy to acquire a calibration board provided with good conductivity, high precision and universality for different magnifications. We get the calibration board (see Figure 2). Although this is similar in appearance to the traditional checkerboard calibration board, it cannot accurately obtain the corner points using traditional calibration procedures, which brings great difficulties to calibration in SEM.

![Figure 2. Calibration board image: (A) Partial enlarged detail of image; (B) Partial enlarged at 500X magnification in SEM.](image)

In general, we need to overcome the following issues, including: 1) The corners caused by noise are not clear (see Figure 2(a)); 2) Automatically identify the point features between large squares to avoid the interference of small squares (see Figure 2(b)); 3) As the tilt angle changes, part of the image is blurred when part of the image is clear.

3. Calibration Method
In this section, a new method based on center point extraction is presented, in order to solve the matter of the corner extraction in traditional calibration procedure [11] using the above calibration plate. Detailed descriptions about the method are presented. It consisted of four parts. Firstly, it is introduced that for automatically extracting the center-points. Second, the homographic matrix is estimated by the center-point features. Thirdly, the distortion coefficient is estimated by performing a nonlinear optimization, utilizing the distortion model. Finally, all the full intrinsic and extrinsic parameters of the SEM are obtained by decomposing the homographic matrix. Our method can perform accurate
calibration even in the situation, commonly happened in a SEM, where the calibration plate is contaminated or partially blurred.

3.1. Automatic center-point feature detection
After an image of the calibration pattern is captured, we detect the point feature firstly. We will introduce the algorithm into three parts, in order to effectively show the main process of the automatic feature detection algorithm.

![Figure 3. Procedures of automatic center-point detection: (A) Image after image enhancement; (B) binary image; (C) Two straight lines at the edges; (D) Grid image with all interference removed.]

1) Preprocess: After capturing the calibration pattern image, top hat transform to lessen inhomogeneity of illumination and contrast stretching to enhance contrast (see Figure 3(a)). Next, Gaussian function in which Gaussian kernel is three smooth the image. At last, convert the image to the binary one with the Ostu threshold (see Figure 3(b)).

2) Remove the two straight lines at the edges: The open operation was applied to make cells in grid unconnected. Then, remove all small areas whose area is less than a certain value so that two straight lines at the edges remained (see Figure 3(c)). After the two lines in the image applied the dilate operation perform logical operation with the binary image. Thus, only grids are left in the image.

3) Centerpoint feature detection: A series of morphological operations, e.g., fill the small holes in the grid, remove the rags, will be performed. A 'cleaning' binary image of the grid can be obtained (see Figure 3(d)). Extract and label each connected part based on connectivity. Finally, center-point of each grid can be detected by calculating the centroid of each square.

3.2. Homography evaluation
We assume the calibration board plane is on $z_w = 0$ of the world coordinate system, and then denote the $i^{th}$ column of the rotation matrix $R$ by $r_i$ [11]. From (3), we have

$$
\begin{bmatrix}
    u \\
    v \\
    1
\end{bmatrix} = K \begin{bmatrix}
    r_1 & r_2 & r_3 & t
\end{bmatrix} \begin{bmatrix}
    x_w \\
    y_w \\
    0 \\
    1
\end{bmatrix} = K \begin{bmatrix}
    r_1 & r_2 & t
\end{bmatrix} \begin{bmatrix}
    x_w \\
    y_w \\
    1
\end{bmatrix}
$$

(7)

Let us still use $X$ to denote a point on the calibration board plane, but $X = (x_w, y_w)$ since $z_w$ is always equal to 0. According to the distribution of white blocks, we can assume the coordinates of each center point, from left to right and from top to bottom in turn, as follows. $X_1 = (1,2), X_2 = (1,4), X_3 = (1,6), X_4$
\( (1,8), X_3 = (1,10), X_5 = (2,1), X_7 = (2,3), \ldots, X_{50} = (10,9) \). Therefore, the \( 3 \times 3 \) homography matrix \( H \) can be estimated by center-point feature.

### 3.3. The estimation of intrinsic and extrinsic parameters

The distortion coefficient is estimated based on static distortion model by performing a nonlinear optimization. All the full intrinsic and extrinsic parameters of the SEM are obtained by decomposing the homographic matrix [11].

### 4. Experimental Results

In the experiments, a Carl Zeiss EVO MA15 SEM has been used to validate the developed calibration method. There is a platform in SEM, including movement in x-axis, y-axis and \( \gamma \)-axis directions, 360\(^\circ\) rotation and tilt range from -5\(^\circ\) to 50\(^\circ\). A multi-scale planar calibration pattern is used in the calibration, where there is a checkerboard structure in a square is a part of a larger checkerboard (see Figure 2(b)). The minimal square is 1um. The set of calibration images whose size is \( 3072 \times 2304 \) pixels have been acquired within the SEM with 50x magnifications.

![Figure 4](image-url)

Figure 4. Comparative experiment of automatic point detection: (A) Enlarged detail image of traditional corner detection; (B) Center-point detection.

To test the effectiveness and reliability of the proposed method, a set of comparative experiments are conducted. We use the traditional corner detection method to perform corner detection on the original image (see Figure 4(a)), and compare it with the method of center-point extraction proposed in this paper (see Figure 4(b)). It can be seen that due to the influence of the corner points of the small grid and noise, the extracted corner points are not in the correct position, and the deviation is large, which will cause the calibration result to be inaccurate or even no solution.

Twenty photos of the calibration board are taken from different views via controlling the platform in the SEM. Then, calibrated it using the method proposed in this paper. The calibration results are as follows. Table 1 shows the estimated calibrated intrinsic parameters \( f_x, f_y, u_0, v_0 \) and the re-projection error \( \|e\| \) in pixel. Table 2 shows the calibrated radial distortion parameter \( k \), tangential distortion parameter \( p_1, p_2 \).

| Mag. (×) | \( f_x \) | \( f_y \) | \( u_0 \) | \( v_0 \) | \( \|e\| \) |
|----------|--------|--------|--------|--------|--------|
| 50       | 34392.0| 33847.8| 1535.5 | 1151.5 | 0.27   |

**Table 1.** Calibration results on intrinsic parameters.

| Mag. (×) | \( k \) | \( p_1 \) | \( p_2 \) | \( \|e\| \) |
|----------|--------|--------|--------|--------|
| 50       | 1.5    | 0.0071 | -0.086 | 0.27   |

**Table 2.** Calibration results with distortion.

At last, re-projection error is used to evaluate the accuracy of the calibration results. It calculates the distance between the original point on the plane of the calibration board and the point, which is obtained by re-projecting the point on the image plane onto the calibration board plane through the calibrated model. It is distribution of the extracted center-point of each image is shown in the Figure 5.
5. Conclusion
In this paper, we have presented a practical method for the calibration of a SEM with a multi-scale planar calibration board. This method using center-point detection instead of corner detection. Preprocess of image, from one step of the method we presented, can effectively reduce the effects of environmental factors, such as light and noise, on image quality. The small grid is merged into a large square through morphological processing to avoid the influence of corner points between the small square. The calibration plate, even though, contaminated by dust, the point based features are more robust than the corner-based feature. Thereby, this improve the accuracy of point detection and enhanced robustness in the case of noise and blurred images. There are main intrinsic and extrinsic parameters, including the magnifications of a SEM, then solved step by step. Experimental results show that the proposed method is effective and reliable for the calibrating of the SEM. Future work will perform pose estimation and three-dimension reconstruction.

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