An online automatic method for correction of piezoelectric scanner*

Yingzi Li
Department of Physics, Beihang University
Beijing, China
e-mail: yingzilee@163.com

Wenliang Liu
Department of Physics, Beihang University
Beijing, China

Baocheng Hua
School of Instrumentation Science and Opto-electronics Engineering, Beihang University
Beijing, China

Jianqiang Qian**
Department of Physics, Beihang University
Beijing, China

Yuan Li
Department of Physics, Beihang University
Beijing, China

Yong Yang
Department of Physics, Beihang University
Beijing, China

Abstract—A novel online auto-correction method is proposed in this paper, according to the nonlinearity and hysteresis of Atomic Force Microscope (AFM) piezoelectric ceramics scanner. In this method, an automatic positioning algorithm is invoked to get the same characteristic points from the forward and backward scanning line; these points are used to calculate the distortion factors to realize image correction. Mathematical derivation of the correction principle is given, and automatic positioning algorithm based on successive template comparison is introduced. Finally situations may cause invalidation of the method are discussed and solutions are given. Practice proves that the method is effective and can be applied in AFM automation.

Keywords- AFM; Nonlinearity; Hysteresis; Correction

I. INTRODUCTION

Since its inception in 1981[1,2], the scanning probe microscope(SPM) has held great promise for investigate the morphology and the local properties of the solid body surface with sub-nanometer resolution. Most SPMs, such as scanning tunneling microscope and atomic force microscope use piezoelectric actuators(piezoceramics) as scanner. The advantages and disadvantages of piezoelectric actuators were discussed by widely literature. According to its four movement error source: nonlinearity, hysteresis[3], creep[4,5] and aging[6], corresponding calibration and correction technologies were studied by many researchers, including hardware method, pre-calibration, post-correction, etc[7-12]. All these method described above have some deficiencies. For example, the software method need artificial extract characteristic points; the hardware method use capacity feedback, not only increase the size and cost of the instrument, more importantly, the feedback will limit the precision of the machine, theoretically, no hardware feedback device have the same precision as AFM scanner; the pre-calibration method use optical lever to identify the distortion factors of the scanner, it need to re-calibration if the scanner or the environments is changed.

A novel automatic method is introduced in this paper, mainly for nonlinearity and creep correction by software.

The advantages of this method compare to those described in previous literatures are: it can complete automatically without human intervention; the sample is not required to be standard raster or simple structure, it can be applied to detect arbitrary structure, practice prove that even a curve is too complex to identify artificial, it can locate precisely; replace scanner has no effect on it, it has great compatibility; there is no limit on the measurement accuracy.

This method can be applied in AFM automation or more humanist commercial image correction software.

II. MATHEMATICAL PRINCIPLE OF CORRECTION

Figure 1. Voltage-displacement curve of piezoelectric tube

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** Corresponding author. E-mail: qianjq@buaa.edu.cn

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Voltage-displacement curve of piezoelectric tube shown as fig.1, this curve shows the characteristic of nonlinearity and creep of piezoelectric ceramic materials very clearly. \( f(V) \) is the forward curve and \( g(v) \) the backward, which \( X \) is the piezoelectric tube’s displacement and \( V \) is the applied voltage.

According to Taylor expansion, it can be expressed as follow under cubic fitting approximation:

\[
\begin{align*}
X &= f(V) = aV^3 + bV^2 + cV + d \\
X &= g(V) = AV^3 + BV^2 + CV + D
\end{align*}
\]

(1)

The origin of voltage will lie in the center without bias voltage, so it can set the symmetric positive and negative voltage, in this case, curve similar to meet:

\[
f(V) = -g(-V)
\]

(2)

By (1) and (2) available:

\[
a = A, b = -B, c = C, d = -D
\]

(3)

In the normalized condition, there are:

\[
\begin{align*}
f(-1) &= -1 \\
f(1) &= 1
\end{align*}
\]

(4)

Get:

\[
\begin{align*}
a + c &= 1 \\
b + d &= 0
\end{align*}
\]

(5)

Let be

\[
\begin{align*}
e' &= c - 1 \\
C' &= C - 1
\end{align*}
\]

(6)

Formulate (1) can be changed into:

\[
\begin{align*}
X &= f(V) = aV^3 + bV^2 + c'V + d + V \\
X &= g(V) = AV^3 + BV^2 + C'V + D + V
\end{align*}
\]

(7)

It separates the ideal linear curve and the distortion curve.

Put (3) (5) (6) into (7) to get:

\[
\begin{align*}
X &= f(V) = (V^3 - V)a + (V^2 - 1)b + V \\
X &= g(V) = (V^3 - V)a + (1 - V^2)b + V
\end{align*}
\]

(8)

From the formula (8) can see that if distortion factors \( a \) and \( b \) equal zero, it will be the ideal case. Subtracting the two equations of the (8) can get:

\[
(x_3 - x_2)\alpha + (x_2 - 0)\beta + \gamma = (x_3 - x_2)\alpha + (1 - x_3)\beta + \gamma
\]

(9)

Which \( f \) represents forward and \( b \) represent backward.

As long as finding out the points \([x_{f1}, x_{f2}, \ldots, x_{fn}],[x_{b1}, x_{b2}, \ldots, x_{bn}]\) which represent the same location of sample in forward and backward scan line coordinate. It can easily solve the distortion factors.

The range of distortion factors of the piezoelectric ceramics material which utilized as scanner is shown below:

\[
\begin{align*}
-0.1 < a < 0.1 \\
0 < b < 0.2
\end{align*}
\]

(10)

III. AUTOMATIC POSITIONING ALGORITHM

The analysis shows that the key point of the method is to calculate the distortion factors from the original forward and backward scanning line, and the difficulty is locate the same points accurately and automatically, as shown in fig.2.

![Figure 2](image)

The ideal solution need to meet the three requirement as follow: firstly, locate accurately. Secondly, the locating points should be one-to-one correspondence, dislocation is not allowed. The third, fault tolerance must be strong enough to deal with complex scanning line.

The successive template comparison algorithm is proposed and it solves the problem well.

The basic thinking of the algorithm is shown as fig.3.

![Figure 3](image)

First divide the backward scanning line into \( N \) segments equally, there are \([b0b1],[b1b2],\ldots,\ldots,\ldots,\ldots\) etc. Because of the scaling of the forward and backward scanning line, let \( b0 \) and \( f0 \) as starting points, \([b0b1],[b1b2]\) as template and search the corresponding segment \([f0f1]\) in forward line to match \( b0b1 \). Then let \( b1 \) and \( f1 \) as next starting points, \([b1b2],[b2b3]\) as template and search \([f1f2]\) to match it and go on until all segmentation.
points in backward line find the corresponding points in forward line.

![Figure 3. the schematic diagram of the successive template comparison algorithm](image)

And now introduce how to realize each precise location by template match. From mathematics, it is to compare the similarity of two curves, and abstracted to compare the similarity coefficient of two discrete datasets. The product moment correlation (Pearson correlation coefficient) is used as evaluation function. Its mathematical expression is as follow.

$$r = \frac{\sum XY - (\sum X)(\sum Y)/N}{\sqrt{\sum X^2 - (\sum X)^2/N} \cdot \sqrt{\sum Y^2 - (\sum Y)^2/N}}$$

(11)

To realize precise positioning, it needs a search process, the schematic diagram shown as fig.4.

![Figure 4. the schematic diagram of search](image)

This process can be concluding as: determine fn by bn-1, fn-1 and fn. First assume fn satisfy [fn-1 fn] = [bn-1 bn], then get the search interval [Ps, Pe] by OSL (offset left) and OSR (offset right), calculate the similarity coefficient of curve [bn-1 bn] and curves [fn-1Ps], …, [fn-1Pe]. The maximum similarity coefficient of these OSL+OSR times calculations lead to the best match result [fn-1Px], and Px is the corresponding point of bn, namely Px is the fn which need to be determined by bn-1, fn-1 and fn.

Because of the requirement that the sample points of two datasets must be the same to calculate their similarity coefficient, curves [fn-1Ps],…,[fn-1Pe] must be scaled to the same length of curve [bn-1bn]. Simple linear interpolation is used in this article to meet this requirement.

IV. DISCUSSION AND CONCLUSION

Fig.2 shows the positioning result of a complex scanning line obtained by automatic positioning algorithm, the upper part of the figure is backward line and lower part if forward line, the locating points is B [64,128,192,256,320,384,448] and F [84,163,233,300,357,413,463], the distortion factors are a=0.0532, b=0.0807.

Fig.5 shows the X-axis correction of a 10um standard raster image.

![Figure 5. Forward and backward standard raster images before and after correction, upper-left is original forward image, upper-right is original backward image, lower-left is corrected forward image and lower-right is corrected backward image.](image)

Fig.6 shows the same section line of forward and backward before and after correction of fig.5. the upper part are original forward and backward section line, and it shows nonlinearity and hysteresis very clearly, the lower part are section line after correction, the forward curve and backward curve coincide very well, it means the errors are eliminated, it prove that the method is effective.

Some extreme situations will cause algorithm ineffective,

![Figure 6. the same section line of forward and backward before and after correction](image)

shown as fig.7. In this case if the length of template is not right, it will lead to some segments (for example segments before peak in fig.4) get wrong match because of information insufficiency. The solution is to use multi-scale match, by change the length of template to make it contains some characteristics (for example the peak in fig.7) to ensure the validity of the algorithm.

Fig.7 shows the Y-axis correction of a 5um standard raster image.
More extreme situation may be caused by scanner error or extreme flat of some sample region, the scanning line with too less information to complete the positioning (in these cases it can’t be identify artificial neither). But these situations will make the locating points and distortion factors out of the normal distribution range. So a redundant subroutine is required to eliminate these situations until the locating points and distortion factors fell into the normal range.

Theoretically, all X-axis scanning line have the same distortion factors; X-axis distortion is independent from Y-axis. But our research shows that different distortion factors will be got when use different section line, although the differences between them are slight. It means that the scanner has cross coupling error between X-axis and Y-axis, how to solve this problem need further research, but this subject is beyond the discussion of this article.

The result of image correction used this method is as good as use hardware feedback; it proves that the mathematics model and algorithm solution is correct. It can be used online before scanning to get the distortion factors of piezoelectric scanner and make the voltage-displacement table to correct the nonlinearity and hysteresis of the scanner. The thinking of the method not only can be used in this situation described in this paper but also can be used widely in machine vision process.

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