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An On-line Scanning Time Allocation based Variable Speed Scanning Method for Atomic Force Microscopies

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***Abstract*—The low scanning speed for atomic force microscopies (AFMs) restricts its further applications, where fast scanning or real-time imaging is required. In some cases (e.g. real-time imaging), repeated scanning tasks on the same area are expected. For this specific application, an on-line scanning time allocation based variable speed scanning method is proposed here to enhance the scanning speed. Specifically, for the repeated scanning tasks, the scanning time for each detected point is intelligently allocated with the information from the afore-scanned image and the previous line in the currently-scanned image, according to the sample surface roughness with the consideration of vertical subsystem control dynamics and horizontal positioning accuracy; then for the repeated scanning tasks on the same area, more scanning time can be allocated to the rough area to achieve better imaging performance. This variable speed scanning method can avoid a waste of time on some flat areas, therefore the imaging time can be shortened. The experimental results fully demonstrate the efficacy of this scanning method to enhance the imaging speed and quality.**

Keywords—atomic force microscopy (AFM); variable speed scanning; repeated scanning tasks; fast scanning

I. INTRODUCTION

The atomic force microscope (AFM), invented by G. Binnig in 1986 [1], has been one of the driving tools in nanoscience and nanotechnology [2, 3]. The main applications include nano-scale imaging, nano-scale manipulations, and material modulus detections [4-6], etc. AFM shows some advantages like no vacuum environment is needed. In fact, AFM can be used in both atmosphere and liquid. And the sample preparation is convenient, no electric conduction is needed, which is the restriction for scanning tunnel microscopies (STM) [7].

AFMs have been widely used. However, some drawbacks still limit its further applications. One of the bottleneck problems is its over-slow imaging speed. Recently, about 1 minute is required to obtain an accurate topography image over 10um scanning scope or more. Therefore, how to speed up the imaging process of AFMs has drawn the attentions of many researchers.

Currently, the approaches to enhance the imaging speed can be classified into two catalogues. The first catalogue considers the hardware components [8]. Obviously, the components with sufficient fast response can achieve high imaging speed [9]. In order to obtain the fast response character for the components, some sophisticated hardware mechanisms are elaborately designed [10, 11]. In [12], an interesting dual Z-axis positioner is proposed, which consists of a long range, relatively low response piezo-actuator and a short range fast response piezo-actuator. It successfully enhances the control bandwidth and imaging speed. A flexure-based X-, Y-, Z-axes nanopositioner is elaborately designed in [13] with such high resonant frequency, that the high scanning speed is achieved. It is straight forward to see that the work on improving the hardware components involves much complication and cost, in spite of its direct efficacy [14]. With this consideration, many researchers focus on the software aspect, the second catalogue, which includes some advanced control algorithms [15-17] and novel tricky scanning methods [18]. As generally known, the AFM tip is driven to scan through the sample in a raster fashion, the scanning time allocated to each detected point is the same [19]. However, the common situation is that researchers only take interested in some part of the sample. Therefore, it is a waste of time to spend time on uninteresting area scanning. With this consideration, many researchers have proposed novel scanning schemes to substitute the conventional raster fashion constant speed imaging method [20]. In [21], an auxiliary optical microscopy is firstly adopted to find out the interesting area, then the AFM tip is driven to scan through only the interesting area with the benefit of shortening the imaging time. In [22], P.I. Chang et al. presented a novel scanning method to drive the tip along the string-like samples to get its topography data at high speed. Y. Zhang et al. proposed a control error based variable speed scanning method, which allocate scanning time properly can achieve very high speed when the sample has much flat area [23]. Additionally, some other elaborately designed scanning schemes can be found in [24, 25].

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There is one specific application, in which AFMs are utilized to repeat scanning on some part of the surface continuously to detect the real-time variation, which is expected in some biological applications for real-time observation [26]. Some exciting results have been published in [27], where a high speed piezo-scanner is well designed and a passive technique is employed to damp the first resonant mode, the scanning speed reaches 10 frames per second. However, the scanning scope is usually too small (e.g. under 1um). In this paper, an on-line scanning time allocation based variable speed scanning method for AFMs is proposed, which can effectively speed up the repeated scanning process and is potential to implement the large area (e.g. ≥ 10um) real-time imaging. Specifically, the scanning time for each detected point is intelligently allocated with the information from the afore-scanned image and the previous line in the currently-scanned image, according to the sample surface roughness with the consideration of vertical subsystem control dynamics and horizontal positioning accuracy; then for the repeated scanning tasks on the same area, more scanning time can be allocated to the rough area to achieve better imaging performance. This variable speed scanning method is well implemented and validated with experimental results.

The remainder of this paper is organized as follows. Section II briefly introduces the working principle of typical AFM systems. In section III, the proposed on-line scanning time allocation based variable speed scanning method will be described in detail. And some experimental results are included in section IV. Finally, section V gives the conclusion of this paper.

II. BRIEF DESCRIPTION TO AFM MECHANISM

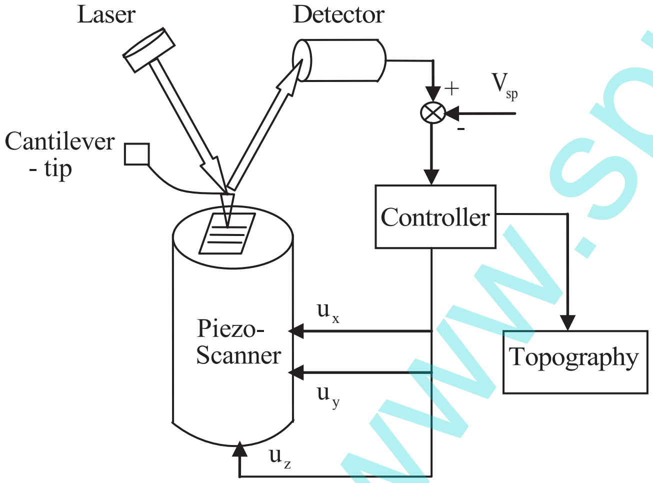


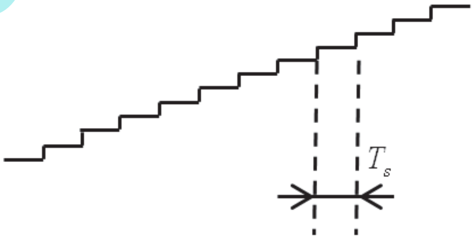
Fig. 1. Schematic diagram of a typical AFM system.

As shown in Fig. 1, the typical AFM system is mainly consisted of four parts: tip-sample interaction, laser and position sensitive detector (PSD), error based controller (e.g. PID controller), and piezo-scanner. With the cooperation of horizontal positioning and vertical tracking, some control signals (e.g. control inputs and control errors) are gathered and analyzed to generate the sample surface topography image.

In vertical subsystem, it works on the basis of a feed-back loop control system. The cantilever tip is regulated to track along the sample surface to collect the topography information. The commonly employed two modes for AFMs are contact mode, which aims to keep the interaction force between tip and sample being constant during the scanning process, and tapping mode, which is to regulate the oscillation amplitude of the cantilever being constant [28].

In horizontal positioning subsystem, the sample is carried by the piezo-scanner to go along a pre-set trajectory, which is usually a raster fashion pattern shown in Fig. 2(a), and in X-axis the piezo-scanner is driven by triangular or staircase waveform control input, as in Fig. 2(b). The width of the staircase T_s is the scanning time for each detected point. The scanning speed is constant along the trajectory and the detecting time for each point is also constant and equal. The innovation in this paper is to break up the restriction on constant T_s, and give a rational allocation of scanning time to each point according to the information from afore-scanned image and the previous line in currently-scanned image.

(a) Raster fashion pattern trajectory for sample scanning.



(b) Staircase waveform control input for piezo-scanner in X-axis.

Fig. 2. The raster fashion pattern scanning trajectory and X-axis staircase control input.

III. DETAIL DESCRIPTIONS FOR VARIABLE SPEED SCANNING

a) General scheme

Now the task is to repeat scanning on the same area continuously. Commonly processing method is to regard each frame task as mutual independent. Although they are scanning on the same area, they have to scan totally anew as if they know nothing about this area. In fact, from afore-scanned image, it is known that some areas are much rougher, while some others are flat. Therefore, with the total scanning time fixed, more time can be allocated to the rough area to get more accurate topography image. On the other aspect of keeping the similar image quality, the scanning speed can be enhanced.

With the consideration above, the on-line scanning time allocation based variable speed scanning method is proposed here, with the scheme diagram shown in Fig. 3. The main steps include: 1) sample surface is normally scanned and the topography is calculated first; 2) with the virtual AFM system [29], the ideal time needed to stabilize the vertical subsystem for each point can be estimated with the afore-scanned image; 3) the scanning time can be allocated with the information of both the afore-scanned image and the previous line in the currently-scanned image; 4) the time allocation is smoothened with Gauss weighted mean to reduce the vibration; 5) the repeated scanning task can be conducted with the newly obtained scanning time allocation, and then roll back to 2) or terminated.

b) Ideal time estimation to stabilize the vertical subsystem

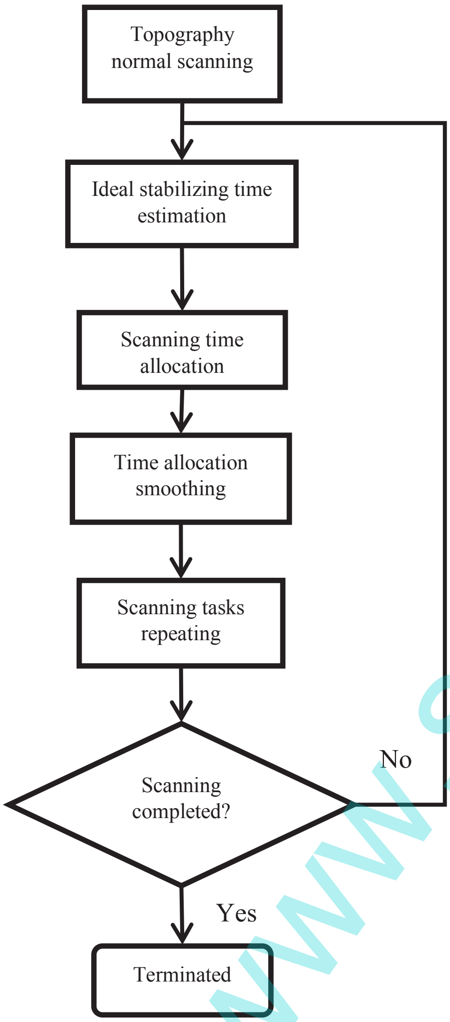


Fig. 3. The scheme diagram for the proposed variable speed scanning method.

For each detected point, it takes some time to stabilize the vertical subsystem to get into steady state. The ideal time needed can be estimated from the virtual AFM system [29], the parameters of which are identified from the real AFM apparatus [30]. When the tip moves from one point to another, the height deflection on the sample surface, causes some control error, noted as e, which then actuates the feedback control loop to stabilize the system. The control error dynamics are shown in Fig. 4. When the control error enters an appropriate region, it is regarded as stabilized. The sampling period is noted as T, the same with the real sampling time for the AFM apparatus in experimental parts. The criterion to evaluate whether the system gets steady is that, a continuous sequence of control errors, $e(t), e(t+T), e(t+2T)......, e(t+(N-1)T)$, which is regarded as sliding window are all in the bound of α, which is defined as a threshold:

$$\left|e(t+kT)\right| \le \alpha;\ k = 0, 1, ..., N-1 \tag{1}$$

The time t is the ideal stabilizing time on this point.

One consideration in Equation (1) is how to choose the sequence length N. In Fig. 4, the resonant period from peak to peak is T_r, which can be calculated from the piezo-scanner dynamics [30]. Then $\frac{1}{2}T_r$ is adopted as the sliding window [23]

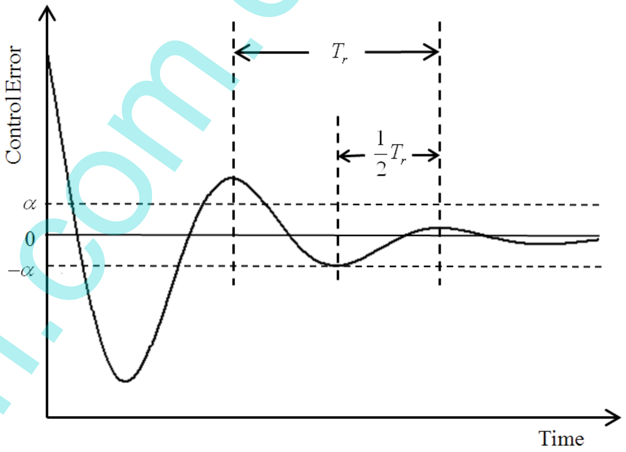


Fig. 4. Control error dynamics for vertical subsystem stabilization.

to ensure that one peak will be included. Therefore the sequence length N is chosen as:

$$N = \frac{1}{2}\frac{T_r}{T} \tag{2}$$

With the analysis of the afore-scanned image, the ideal stabilizing time for each detected point can be well obtained.

c) Scanning time allocation

Now come to the step of scanning time allocation. Intuitively, the scanning time allocated for each point should be proportional to the ideal stabilizing time from the afore-scanned image. However, sometimes it faces two problems:

1. The sample surface may vary largely between the two frame scanning tasks.
2. Due to some causes, the whole positioning excursion between the two continuous frame tasks can not be neglected.

In the two cases, it is no longer suitable to allocate scanning time only with the afore-scanned image alone, because the large variance between the two images needs to be considered. In fact, it can be effectively addressed by combining the afore-scanned image with the newly obtained information on the previous line in the currently scanned image.

It is rational to suppose that the topography in current line is similar with the previous line. Therefore, the time allocation can be calculated from the combination between the same line in afore-scanned image and the previous line in the currently scanned image.

The scanning time for the whole image is noted as T_{total}, the resolution of the image is noted as $res \times res$. Therefore the time spent on one row is:

$$T_{row} = \frac{T_{total}}{res} \tag{3}$$

The point in the i-th row and j-th column is noted as P_{ij}, and the stabilizing time estimation for P_{ij} in the afore-scanned image is denoted as t_{ij}^{p}. Similarly, the ideal stabilizing time for $P_{(i-1)j}$ in the currently-scanned image is denoted as $t_{(i-1)j}^{c}$. Now the time allocation for the i-th row in currently scanned image can be calculated as:

$$T_{ij}^{1} = \left[\frac{t_{ij}^{p}}{\sum_{k=1}^{res} t_{ik}^{p}} \beta + \frac{t_{(i-1)j}^{c}}{\sum_{k=1}^{res} t_{(i-1)k}^{c}} (1-\beta) \right] T_{row} \tag{4}$$

Where T_{ij}^{1} is the time allocated to the point P_{ij} in currently scanned image, and the factor β is a tradeoff between the information of the afore-scanned image and currently-scanned image. It is shown that the time allocation is on-line process, calculated one line by one line.

One consideration here is how to choose the tradeoff factor β. The underlying idea is that, if the topography of the (i-1)-th row in the afore-scanned image is in accordance with that in currently-scanned image, then β would be chosen tend to 1, because the variance between the two images is small; otherwise, β would be chosen tend to 0.

The quantitative calculation for β is shown here. The topography height deflection between two adjacent points $P_{(i-1)j}^{p}$ and $P_{(i-1)(j+1)}^{p}$ is noted as $\Delta h_{(i-1)j}^{p}$ in the afore-scanned image. Similarly, $\Delta h_{(i-1)j}^{c}$ is defined for currently-scanned image. The height variance between $P_{(i-1)j}^{p}$ and $P_{(i-1)j}^{c}$ is noted as $d_{(i-1)j}$. Therefore, the variance factor γ can be defined and calculated as:

$$\gamma = \frac{2\sum_{k=1}^{res} d_{(i-1)k}}{\sum_{k=1}^{res} \Delta h_{(i-1)k}^{p} + \sum_{k=1}^{res} \Delta h_{(i-1)k}^{c}} \tag{5}$$

The factor γ reflects the variance degree of the one-line topography between the (i-1)-th row in afore-scanned image and currently scanned image.

Therefore, the tradeoff factor β in Equation (4) can be empirically chosen as:

$$\beta = \begin{cases} 0.8 & \gamma < 10\% \\ 0.5 & 10\% \le \gamma < 30\% \\ 0.2 & 30\% \le \gamma \end{cases} \tag{6}$$

d) Time allocation smooth

The scanning time is well allocated from Equation (4), but one problem is that, the allocated time for some adjacent points in the same row may have great difference. This would cause vibration to the piezo-scanner.

Therefore smooth processing with Gauss weighted mean, also known as Gauss filter, is introduced here as shown in Equation (7).

$$T_{ij}^{2} = \sum T_{ij}^{1} g(k);\ k = j-m, j-m+1, ..., j+m \tag{7}$$

Where T_{ij}^{2} is the allocated time for P_{ij} after the Gauss weighted mean. $g(k)$ is the Gauss weighted value, m is the filter window length which is chosen as 5 in the experimental part.

With the newly obtained scanning time allocation, the repeated scanning tasks can be conducted to get more accurate topography image.

IV. EXPERIMENTAL RESULTS

To verify the validity of the proposed on-line scanning time allocation based variable speed scanning method, some experiments are conducted on the platform of RT-Linux based AFM system, which is shown in Fig. 5. This platform is consisted of a commercial AFM apparatus (CSPM4000, Being-Nano Inc., P.R. China) and a self-implemented RT-Linux based control system [31]. The control period is 50us, equivalent to a high bandwidth of 20KHz. The PI controller with appropriate tuned parameters is utilized to stabilize the vertical subsystem. The scanning sample is chosen as the commonly used calibration gratings (uMarsh Inc. USA) with the nominal height of 84 ± 1.5nm and period of 3um. The scanning scope is 10um and image resolution is 400 × 400 pixels. The one line results comparison between commonly constant speed scanning and the proposed variable speed scanning method is shown in Fig. 6 and Fig. 7, corresponding to 10Hz and 25Hz line frequency respectively. It is shown in Fig. 6(a) and Fig. 7(a) that, the up and down edges of gratings for variable speed scanning are cliffer than that for constant speed scanning. This character is more evident in fast scanning tasks in Fig. 7(a). Therefore, the obtained topography from variable speed scanning is more accordance with the real sample surface. Fig. 6(b) and Fig. 7(b) show the scanning time allocation comparison. We can see that the area where sample surface fluctuates greatly is allocated with more scanning time to stabilize the vertical subsystem.

From the results comparison, it is shown that the proposed method achieves much better scanning performance especially for fast repeated scanning tasks.

V. CONCLUSION

In this paper, an on-line scanning time allocation based variable speed scanning method for AFM system is proposed for the specific application of repeated scanning tasks on the same area. With the information from the afore-scanned image and the previous line in the currently-scanned image, the scanning time is properly allocated to each detected point in the following repeated scanning process. It has effectively enhanced the imaging speed and topography accuracy.

In the future work, we will be trying to break through the restriction of raster fashion scanning pattern, and further shorten the imaging time with compressed sensing techniques.

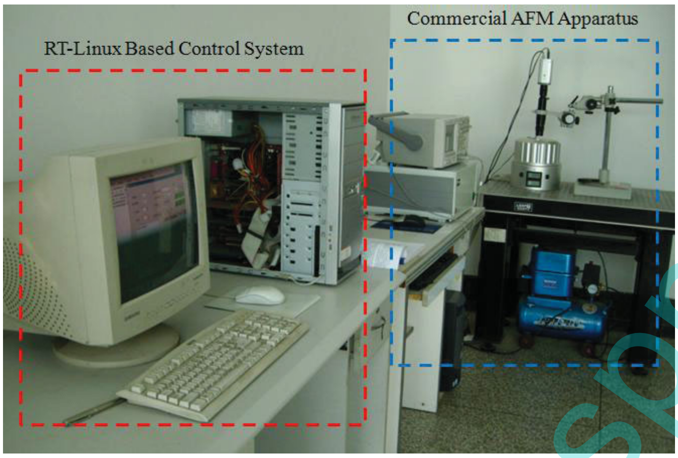
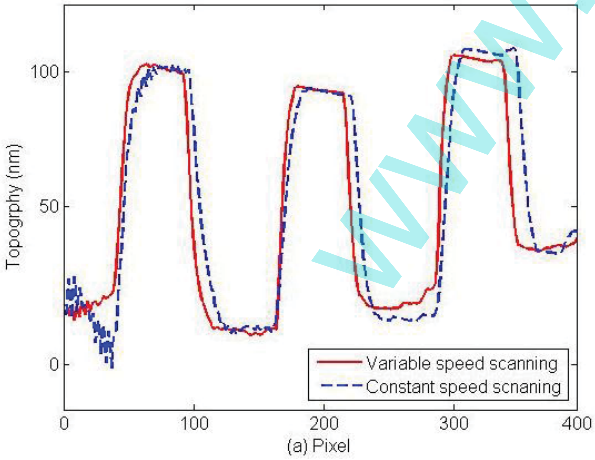


Fig. 5. The platform of RT-Linux based AFM system.



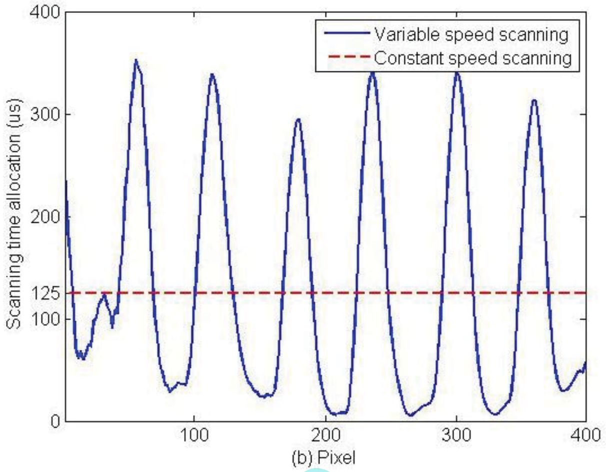


Fig. 6. One line topography results and scanning time allocation for the scanning tasks of calibration gratings, with scanning scope of 10um and scanning frequency of 10Hz.

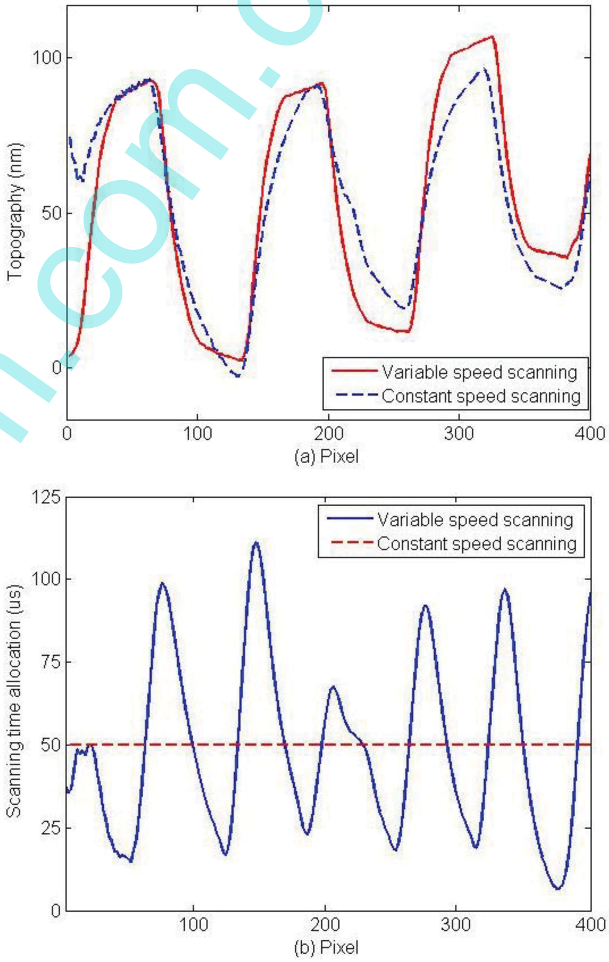


Fig. 7. One line topography results and scanning time allocation for the scanning tasks of calibration gratings, with scanning scope of 10um and scanning frequency of 25Hz.

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