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High-speed large-range dynamic-mode atomic force microscope imaging: Adaptive tapping approach via Field Programmable Gate Array

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***Abstract*— This paper presents a software-hardware integrated approach to high-speed large-range dynamic mode imaging of atomic force microscope (AFM). High speed AFM imaging is needed to interrogate dynamic processes at nanoscale such as chemical reactions. High-speed dynamic-modes such as tapping-mode AFM imaging are challenging as the probe tapping motion is highly sensitive to the highly nonlinear probe-sample interaction during the imaging process. The existing hardware-based approach via bandwidth enlargement, however, results in a substantialy restricted imaging area that can be covered. Contrarily, software-based approach, for example, the recently developed adaptive multiloop mode (AMLM) technique has demonstrated its efficacy in increasing the tapping-mode imaging speed without loss of imaging size. However, further improvement has been limited by the the hareware bandwidth and the online signal processing speed and computation complexity.Thus, in this paper, the AMLM technique is furhter enhanced to optimize the probe tapping regulation and integrated with the FPGA platform to further increase the imaging speed without loss of imaging quality and range. AFM imaging experiment is presented and discussed to illustrate this integrated approach.**

I. INTRODUCTION

In this paper, a control-based imaging technique is proposed and integrated with hardware improvement to achieve high-speed, large-range dynamic-mode imaging. [1] Dynamic-mode, particularly, tapping mode (TM), has become the de facto choice of AFM imaging technique for its high quality imaging quality and subdued sample distortion. [16], [17] However, the imaging speed of TM is rather slow when compared to contact mode, as it is more challenging to maintain the probe-sample contact as the speed increases, especially when the scan size becomes large. [18] Existing efforts in hardware or software (algorithm) innovations to increase the speed of TM imaging [2]–[4] , however, are limited in the speed that can be achieved, or the sample area that can be covered (per image). Thus, this work is motivated to combine both hardware and software improvements together to arrive at high-speed, large-range TM imaging.

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It is challenging to achieve high-speed, large-range TM-imaging. The challenge mainly arises from the highly nonlinear force-distance relation in the probe tapping during TM-imaging [5]. As a result, the amplitude of the probe tapping is sensitive to the probe-sample distance variations, and thereby, can change dramatically upon sudden sample topography variations [6]. Particularly, when the imaging speed increases, quick change of the tapping amplitude can lead to a loss of probe contact, or annailation of the tapping motion completely. As the tapping amplitude must be closely regulated, the loss of contact and/or tapping annailation directly results in a loss of imaging quality, and sample and/or probe deformation. Moreover, during TM-imaging, the tip is vibrated at high frequencies (around the resonane of the cantilever) [7], the delay existing in deciphering the tapping amplitude, also makes it difficult to maintain the tapping amplitude during high-speed imaging. Thus, improving the speed in TM-imaging.

Limitations exist in current efforts to achieve high-speed, large-range TM-imaging. For example, efforts have been pursued to increase the TM-imaging speed via hardware improvements [7]–[9]. The idea is to substantially increase the bandwidth of the overall nanopositioning system along with high-speed data processing, so that the dynamics of the AFM system won't be excited when the scanning speed increases (for the frequencies of the cantilever motion become far below the AFM bandwidth). Although the imaging speed can be signficantly increased, the sample area that can be covered per image is also dramatically reduced by over 2 orders of magnitude (e.g., from 100 μm by 100 μm to $\sim$5 μm by $\sim$5 μm and less [19]), as the displacement range of the actuators inevitably reduces with the bandwidth increase [9]. Alternatively, the imaging speed can be increased — without losing the imaging area — through the development of control techniques. For example, the observer-based techniques [10], [11], [13] have been developed to reduce the time-delay in deciphering the tapping amplitude and better estimate the sample topography. The increase of the TM-imaging speed, however, is rather limited and much lower than that achieved via bandwidth enlargement above [8], [9]. Moreover, the probe-sample interaction force, and thereby, tracking of the sample topography itself, has not been adequately controlled, resulting in a pronounced loss of imaging quality in high-speed TM-imaging (e.g., around 10 Hz scanning).

These limitations of control-based algorithm innovation to TM-imaging, in both the imaging speed and the interaction force, have been tackled in the recently developed adaptive multi-loop mode (AMLM) [1], [12] technique, where an additional feedback loop is introduced to regulate the mean value of the probe vibration, and thereby, the interaction force, and a data-driven online iterative feedforward control is further augmented to the feedback loops for topography tracking. It has been demonstrated via experiments that over an order of magnitude increase of the imaging speed without loss of imaging quality can be achieved, over a large scanning area (over 50 μm) [1] and on various polymer samples [12]. Further increase of the imaging speed—towards those attained via bandwidth enlargement at 100 Hz and higher scanning rate, range, however, has been limited by the hardware bandwidth and the online signal processing speed and computation complexity (in the frequency-domain iterative control alogorithm involved).

The main contribution of this paper is the development of a hardware-software-integrated approach to high-speed large-range TM-imaging. First, the AMLM technique is further extended to further optimize the tapping amplitude regulation, and improve both the efficiency and robustness in online implementation. Specifically, we introduce an online regulation of the tapping amplitude to, unlike all the existing TM-imaging that aims at maintaining a *constant* tapping ampltiude, adaptively adjust the desired amplitude around the optimal value, then a data-driven, time-domain, inversion-based iterative control is proposed to replace the frequency-domain one in the AMLM technique, such that the complicated online computation can be avoided. Then, the feedback errors in both the tapping amplitude and the TM-deflection regulation are accounted for in the desired trajectory (for the iterative feedforward control), thereby, further improving the transitent response in the topography tracking. A Field Programmable Gate Array(FPGA)-based platform is utlized to implement this enhanced AMLM technique with high-speed online signal acquisition and processing. Methods to circumvent the hardare limitations of current FPGA system (e.g., limited onboard memory) are also discussed. Finally, this FPGA-based enhanced AMLM technique is applied to an AFM with higher bandwidth piezoelectric acutation system (nearly 10 times larger than that previously). Such an integrated approach provides a synergetic avenue to merge the advantages of both hardware and software together towards high-speed large-range imaging otherwise much more difficult to attain. Experimental implementation presented shows that TM-imaging at large-range (nearly 20 μm scanning size) and high-speed (80 Hz scanning rate) can be achieved.

II. High-Speed Large-Range Dynamic-mode Imaging: An Integrated Approach

The proposed approach combines imaging algorithm innovations with hardware improvements. During TM-imaging, the cantilever probe is excited by a dither piezo to vibrate near its resonance frequency and tap on the surface constantly [14]. However, the speed of conventional TM-imaging is inherently hampered by the time delay in the tapping amplitude regulation feedback, and the tapping being sensitive to the probe-sample distance due to the highly nonlinearity of the probe-sample interaction force [6]. As the imaging speed increases, loss of probe-sample contact tends to happen when the topography suddenly drops, and the tapping can be completely annihilated around the regions where the topography rises dramatically. The recent developed AMLM technique tackled these issues [1]. However, further improvement has been limited by the hareware limitation and the online signal processing speed and computation complexity (in the frequency-domain iterative control alogorithm). This work aims to address these limitations.

III. Enhanced Adaptive Multiloop Mode Imaging

In this section, the AMLM technique is enhanced (called the *E-AMLM* technique below) in two aspects (see Fig.1): (I)a time-domain data-driven iterative control to replace the original frequency-domain one in AMLM, and (II) account of both the tapping amplitude and the mean value of the cantilver vibration (called the TM-deflection below) in the feedforward tracking of the sample topography, respectively. As in AMLM technique, a feedback control of inner-outer loop structure is integrated to regulate the TM-deflection (see Fig. 1). We start with introducing the feedback control structure first.

A. TM-Deflection Regulation with An Inner-outer Feedback Control Scheme

As in the AMLM approach, a feedback loop is introduced to regulate the averaged (vertical) position of the cantilever vibration (i.e., the TM-deflection). This TM-deflection feedback loop works with the TM-amplitude loop in concert to maintain a stable tapping motion of the cantilever, particularly, when the scanning speed increases. An inner-outer feedback loop is utilized, where outer loop to adjust the TM-deflection setpoint employs the following PID type of control,

$$\begin{aligned} d_{\text{TM\_set}}(j+1) = k_p e_{\text{TM}}(j) + k_{i\text{TM\_set}}(j) \\ + k_d[e_{\text{TM}}(j-1) - e_{\text{TM}}(j)] \end{aligned} \tag{1}$$

$$e_{\text{TM}}(j) = d_{\text{TM\_d}} - d_{\text{TM\_set}}(j) \tag{2}$$

and j = 2, ... ,N-1, where N is the total number of sampling periods per scan line, and k_p ,k_i, and k_d are the proportional, integral, and derivative coefficients, respectively. Initially the setpoint for the outer loop $d_{\text{TM\_d}}$ is set at the mean TM deflection at the starting point of the imaging process.

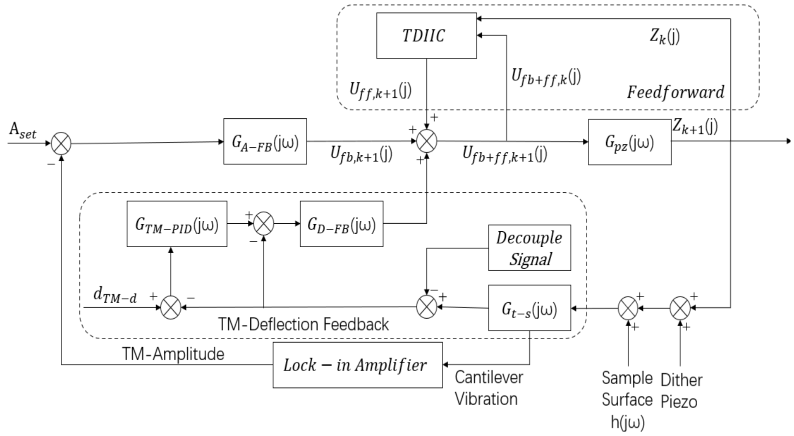

Fig. 1: Schematic block diagram of the E-AMLM imaging technique

Account of the Lateral-to-vertical Coupling

In AFM systems, the TM deflection signal measured can be coupled with and contains x- and y-axes movement of the piezo actuator. To decouple such a coupling effect on the TM-deflection, the TM-deflection signal is acquired by driving the cantilver to scan over the same lateral displacement range and at the same scanning speed as those employed that in the imaging process later, respectively, without touching the surface, i.e., the variation of the TM-deflection measured, if any, will only caused by the lateral coupling effect and not by the sample topography (excluding random disturbances). During the imaging process, the TM deflection signal acquired above will then be substracted from that measured in the imaging process, and the processed signal will be used for control and topography construction.Compared to other model-based approach, this method (called the *free-air scanning method* below) is more effective as the coupling can vary substantially between each engagement (of the cantilever), but remains largely the same during the following imaging process (with the same cantilever mounted and the same enviornment condition).

B. Online iterative feedforward control for sample-topography tracking

To enhance online implementation efficiency of the AMLM technique, we propose the following time-domain inversion-based iterative control (TDIIC) algorithm (to replace the original frequency-domain IIC technique [1]),

$$u_{ff,0}(j) = 0, \tag{3}$$

$$u_{ff,k+1}(j) = G_{inv}(j)h_{k+1,d}(j) \qquad \text{for } j = 0, 1, 2, ... \tag{4}$$

where M is the number of sampling point per scan line, $G_{inv}(j)$ is the iterative gain updated point-by-point, and $h_{k,d}(\cdot)$ is the desired trajectory to track, respectively, and α and β are the corresponding scale factors, respectively.

Specifically, for the (k)th line $h_{k+1}(\cdot)$ is approximated as the vertical displacement of the z-axis piezo actuator on the preceding kth scanline, then updated by accounting of tapping amplitude error and the TM-deflection.

$$h_{0,d}(j) = 0 \tag{5}$$

$$h_{k+1,d}(j) = h_k(j) + \alpha e_{Amp}(j) + \beta e_{TM}(j) \tag{6}$$

Moreover, the iterative gain $g_{inv}(j)$ is updated by using the measured input-output data as

$$g_{inv}(j) = \begin{cases} (1-\lambda)G_{inv,DC} + & \\ \quad \lambda(\frac{u_{ff+fb,k}(j) - u_{ff+fb,k}(j_0)}{h_k(j) - h_k(j_0)}) & |\delta h(j)| \leq \epsilon \\ g_{inv,DC} & \text{otherwise} \end{cases} \tag{7}$$

and $g_{inv,DC}$ is the inverse DC-gain of the z-axis AFM piezo-actuation system where $\delta h(j)$ is the velocity of the probe given by

$$\delta h(j) = h_{k-1}(j) - h_{k-1}(j-1) \tag{8}$$

The aim of the above feedforward control is to speed up the response of the overall control system to sudden rapid changes in the sample topography iteratively. The online adjustment of the iterative gain $g_{inv}(\cdot)$ accounts for the variation of the system gain with the saturation effect considered. The threshhold value is chosen to depend on the probe velocity, as the variation of the gain grows with the probe velocity due to its nonlinear dynamics.

At the beginning of the imaging process, the scheme described above is applied to scan the first line repetitively until the convergence is reached, (i.e. difference of the z-piezo displacement between two consecutive iterations cannot be further reduced). Then the rest of the sample is scanned continuously without repetition.

IV. FPGA Implementation and Discussion

In this paper, a FPGA-based signal processing platform is chosen to implemented the proposed approach by

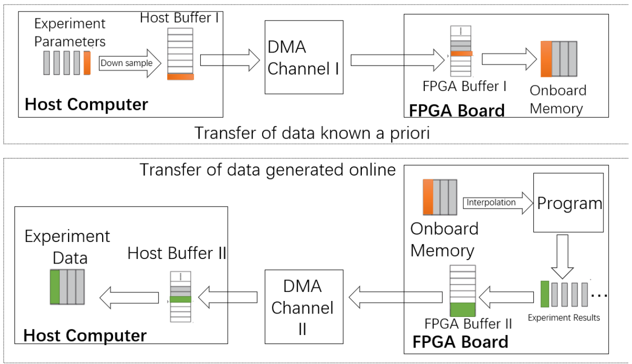

Fig. 2: Schematic block diagram of the method for FPGA transferring (a) large-size data known a priori, and (b) those generated/modified online, respectively.

programming it on a host computer, compiling into logical circuit maps, and downloading to the FPGA board.
Compared to other conventional DAQ systems, FPGA based platform raises constrains that need to be addressed. The main issue is that the onboard memory is limited, thereby cannot store large-size data such as a long desired trajectory or experiment results. For large-size data known a priori (e.g. a desired trajectory), the data can be downsampled on the host computer first before transfer, and then onlince recovered on the FPGA board via interpolation (See Fig.2(a)). For data generated or modified online, they can be transferred to the host computer during the experiment process simultaneously through a buffer-to-buffer structure implemented by the direct-memory-access(DMA) technique, such that the online operations (e.g., sampling and computation) won't be interfered by the data transfer. However, additional care shall be taken as there are only few DMA channels onboard and these channels are half-duplex (i.e., one direction at a time). Thus, when the number of data sets exceeds that of the DMA channels, buffers need to be allocated and assigned with the DMA channels so that the data can be transferred through a queue without overlapping each other or missing data issues.

V. Experimental Demonstration

The proposed imaging technique was illustrated through AFM experiments on a calibration sample. The objective was to demonstrate that high-speed imaging can be achieved with image quality comparing to conventional tapping mode. We start with describing the experimental setup.

Experimental Setup

The experiments were performed on a commercial AFM system (Dimension FastScan, Bruker Inc), where the piezoelectrical actuators can be directly controlled via an external drive, and the cantilever displacement (z-sensor signal) and the force (cantilever deflection) can be directly measured. Labview-FPGA system (NI RIO Device, USB-7856R, National Instrument Inc.) were used to implement the E-AMLM technique on the AFM system. The sampling rate was set at 100 kHz. The calibration sample used in the imaging process is STR3-1800P, Bruker Inc, with 180nm step height and 3μm pitch.

Experimental Implementation

First, to remove the lateral-coupling effect on the TM-deflection, the TM-deflection signal was acquired while the cantilever was scanning under the tapping-mode condition without engagement (called the *false engagement*, i.e., without tip-sample contact). The scanning size was the same as that in the imaging experiment later at 16 μm, and the scanning speeds were the same at those tested later. The TM-deflection measured was used in all following experiments for lateral coupling compensation. Then, the parameters in the E-AMLM method were tuned experimentally. Specifically, the PID paremeters of the TM-amplitude loop were tuned first along with the cut-off frequency of the low pass filter by examing the frequency spectrum of sample topography acquired by conventional tapping mode. Then the PID-like coefficients of the inner-outer-loop of the TM-deflection loop were tuned experimentally. Under the condition that these two loops worked together properly, the TDIIC feedforward control was augumented, where the scaling factors of the TM-amplitude error and the TM-deflection error, respectively, were adjusted by using the known height value of the calibration sample.
During the implementation of the E-AMLM method, at the first scanline the sample was first scanned at low speed (2 Hz) such that the z-axis displacement measured was close to the sample topography, and thereby, can be used to obtain the desired trajectory for the first scanline imaging (see Eq.(6)). Then the scanning speed was increased to the chosen highspeed, and the TDIIC-based feedforward control was augmented to repetively scan on the first line for 4 times. The rest of the imaging area was then scanned continuously without repeitive scanning where the desired trajectory for the TDIIC feedforward was constructed by using the z-axis displacement, the TM-amplitude and TM-deflection error acquired in the preceding scanline (see Eq.(6)). Precision tracking in the lateral x- and y- axes were obtained by using the MIIFC [15] technique, where the lateral scanning tracking error was maintained below 2 % (measured in the relative 2-norm sense), respectively.

Experimental Results and Discussion

Imaging results obtained at two different scanning speeds, 50 Hz and 80 Hz, respectively, were acquired in the experiments for a lateral scan size 16 μ m (50 % of the total scan range). For comparison, the imaging results obtained by using the conventinal TM at low speed of 2 Hz was also acquired, by using the same cantilever and keeping all other experimental conditions the same.
The experimental results obtained are presented in Figs.3 to 7. The lateral-coupling-caused TM-deflection variation

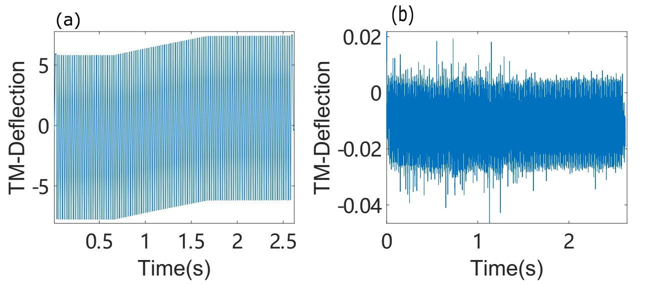

Fig. 3: Comparison of (a) the lateral-coupling-caused TM-deflection measured at the scan rate of 50 Hz, and (b) the TM-deflection after the coupling removal process, respectively.

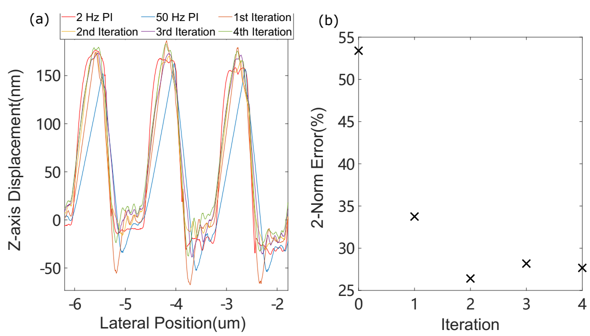

Fig. 4: (a) Comparison of the z-axis displacement obtained by using the E-AMLM with four repetive scanning at the first line to that obtained with PI control at 2 Hz scan, and (b) the tracking eror with respect to the 2 Hz scan in each iteration in relative 2-norm, respectively.

measured for the scan rate of 50 Hz is shown in Fig.3 (a), compared to the free-air-coupling TM-deflection after the coupling-removal in Fig.3 (b), respectively. To examine the convergence of the TD-IIC, the z-axis tracking result of 50 Hz scan obtained by the four iterations on the first scan line are shown in Fig. 4 (a), (only partial line results are shown for clarity in presentation) with comparison to that obtained by using the PI-control at scan rate of 2 Hz, where the tracking error measured in relative 2-norm by using the 2-Hz PI-tracking result as the reference is also shown in Fig.4 (b), respectively. The topography images obtained at the scan rate of 50 Hz by using the E-AMLM technique and the PI control are compared in Fig. 6 (a) and (c), respectively, along with that obained by PI control at scan rate of 2 Hz in Fig. 6 (b). To further examine the topography tracking, the cross-section sample topography profiles at a randomly chosen scan line (marked by the red-dashed line in Fig. 6 (a), (b), and (c)) are also compared in Fig. 5 (a), for the the above three conditions, respectively, where the tracking errors of the 50 Hz E-AMLM and 50 Hz PI control, with respect to the 2 Hz sample profile, are also compared in Fig. 5 (b), respectively. Finally, the sample topography imaging results obtained at 80 Hz scan rate are comapred in Fig. 7 (a), (b) for the E-AMLM technique and PI-controlled TM-imaging, respectively.

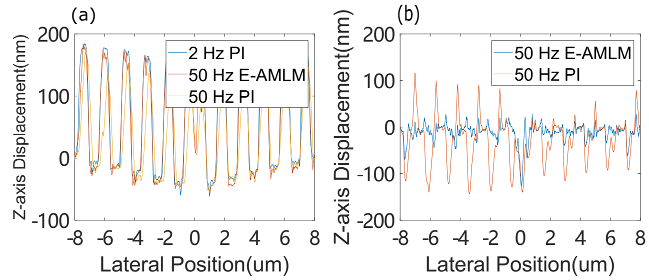

Fig. 5: Comparison of the corresponding topography profile (a) and error of same cross section (b)

The experimental results showed the efficacy of the proposed approach in removing the latera-coupling effect and online convergence in tracking. As shown in Fig. 3, the lateral-coupling-caused fluctation in the TM-deflection was pronounced—the envolop change of the TM-deflection in Fig. 3 (a) caused by the lateral coupling effect was as large as 8V. Such a large change of TM-deflection amplitude was 50 times larger of that due to the topography variation of the calibration sample used in the experiment, thereby, completely swallow the topography variation in the image obtained. By using the proposed on-site free-air scanning method, this lateral coupling effect was completely removed—the fuctuation of the TM-dfelction was now around the noise level with a small mean value around 10 mV. Moreover, convergence was achieved by using the proposed TD-IIC-based feedforward control. As shown in Fig. 4, tracking of the sample topography on the first scanline converged in only 3-4 iterations, with the relative tracking error reduced to 26.4%. The removal of the lateral coupling in the TM-deflection and the rapid convergence in the repetitive imaging on the first scanline directly contributed to the performance of the proposed E-AMLM technique.

The imaging results demonstrated that the speed of tapping-mode, large range AFM imaging can be significantly increased by using the proposed approach. It can be seen that the image quality of the topography obtained by using the E-AMLM technique at 50 Hz compared well to that obtained by TM imaging at 2 Hz (see Fig. 6 (a) and (b)). Both images presented sharp edges of the square-shaped pitches, whereas such shape was distorted in the 50Hz TM imaging result (compare Fig. 6 (c) to Fig. 6 (a) and (b)). This difference can be seen more clearly in the cross-section sample profile comparison in Fig. 5: the topography difference respect to the 2 Hz TM result was 60% smaller when using the proposed technique than that when using the 50 Hz TM imaging. The imaging quality difference (between the proposed E-AMLM technique and the TM-imaging) became more pronounced in the 80 Hz scaning result: The square-shape pitches were largely preserved in the image obtained by using the proposed approach, but largely distorted to fuzzy triangle shape when using the conventional TM-imaging. Therefore, the experimental results demonstrated the efficacy of the proposed approach

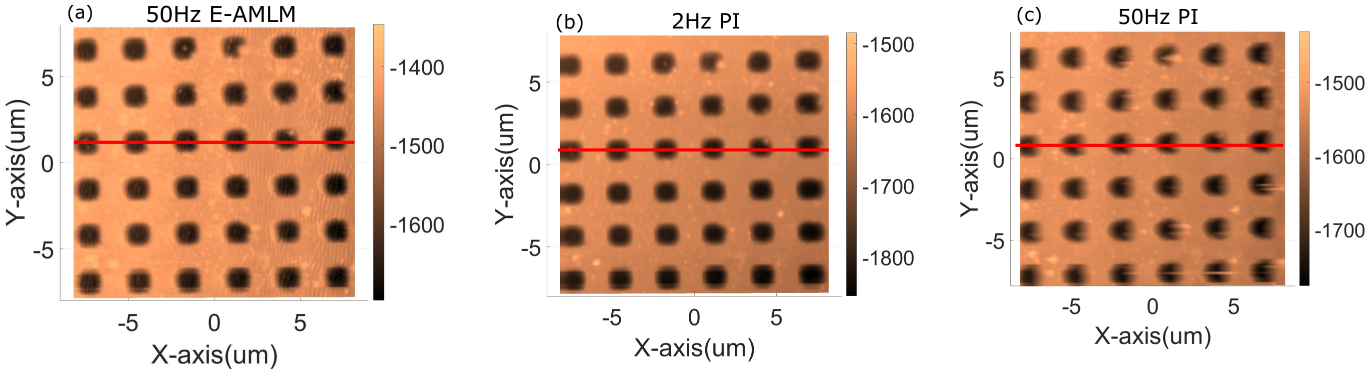

Fig. 6: Comparison of the topography image obtained by (a) the E-AMLM technique at scan rate of 50 Hz, and the PI-control at (b) scan rate of 2 Hz and (c) 50 Hz, respectively.

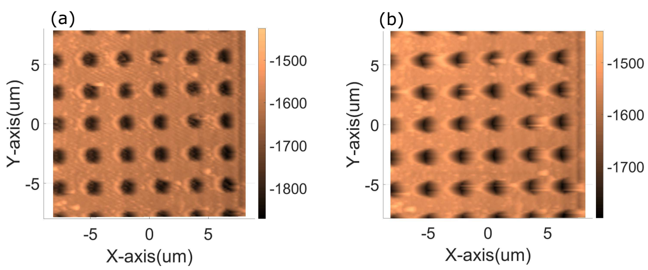

Fig. 7: Comparison of the topography image obtained by (a) the E-AMLM technique and (b) the PI-control at the scan rate of 80 Hz, respectively.

in achieving high-speed large-range tapping-mode imaging on AFM.

VI. Conclusion

A hardware-software integrated approach was proposed for high-speed, large-range tapping-mode imaging on AFM. The recently developed AMLM technique was enhanced and integrated with a FPGA high-speed data processing platform on an AFM system with relatively high bandwidth. Moreover, a time-domain data-driven iterative control(TDIIC) was proposed to replace the frequency domain one in the AMLM technique to improve the online efficiency. The efficacy of the proposed E-AMLM imaging was demonstrated by imaging a calibration sample at different scanning speeds (50 and 80 Hz) in experiment. The experiment results showed that by using the proposed technique, the imaging speed was significantly increased.

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