High Performance Control of Atomic Force Microscope for High-Speed Image Scanning

M. S. Rana, Student Member, IEEE, H. R. Pota, Member, IEEE, and I. R. Petersen, Fellow, IEEE
School of Engineering and Information Technology
The University of New South Wales
Canberra, ACT 2600, Australia.
Email: md.rana@student.adfa.edu.au, h.pota@adfa.edu.au, and i.petersen@adfa.edu.au.

Abstract—This paper presents the design of a model predictive control (MPC) scheme with a notch filter for reducing the tracking error of an atomic force microscope (AFM) by damping the resonant mode of the piezoelectric tube (PZT) scanner. The development of a controller for the AFM imaging and scanning speed is illustrated in this paper. Experimental results show that the proposed controller can increase the scanning speed significantly as compared with the existing PI controller.

I. INTRODUCTION

The atomic force microscope (AFM) has become one of the most versatile tools in the field of nanotechnology. It is capable for generating three-dimensional (3D) images of material surfaces at an extremely high resolution down to the atomic level [1], [2]. The AFMs promise breakthroughs in the areas such as bionanotechnology, nanoparticle characterization, material science, and nanomachining [3]. It is not restricted to imaging in a vacuum environment as are the transmission electron microscope (TEM) and the scanning electron microscope (SEM).

The selective features of the AFM such as the ability of fast and easy sample preparation; air, liquid, and vacuum environments of operation; relatively lower costs; etc., make it an amazing technique of strong preference [4]. There appears to be some scope to improve its performance. The performance of an AFM can be described by the image quality and the scanning speed which are inversely proportional. For this reason a variety of different control methods have been developed to control AFM positioning to generate controlled motion for fast positioning. A basic schematic diagram of the AFM is shown in Fig. 1.

Majority of the commercially available AFMs use a piezoelectric tube (PZT) scanner for \( x-y-z \) positioning. Piezoelectric creep, thermal drift, induced vibration, and hysteresis nonlinearity of the scanner adversely affects the tracking accuracy and speed of operation of an AFM [5]. The use of feedback control techniques other than PI controllers to improve tracking accuracy and scanning speed of AFMs has been undertaken by a number of researchers [5]–[9].

Hysteresis effect is the multivalued nonlinear phenomenon between the applied voltage and the output displacement as shown in Fig. 2(a). It is become noticeable when PZTs are actuated using voltage signals of high amplitudes. On the other hand at low-range scans (i.e., when actuating a PZT with voltage signals of low amplitude), hysteresis can be ignored [10]. Feedback control schemes have been used to compensate for hysteresis in [8], [11], [12]. Creep (see Fig. 2(b)) is another nonlinearity which is noticeable at low frequencies signal. This effect can be severe during slow operation of the AFM. A good number of methods have been proposed to deal with this effect [13], [14]. The most common used approach in earlier AFMs has been to allow sufficient time for the effect of creep to disappear. Mechanical vibration is also responsible for the poor image quality of the AFM and this vibration is created because of the resonant modes in the PZT actuator. To avoid this problem, the scanning speed of AFMs is often kept limited to 1% [5] of the scanner’s first resonance frequency. This vibration can be compensated by proper damping of the resonant modes. Research has been done by several authors on this issue [8], [15], [16].
In this work, we have proposed a MPC-Notch control scheme to reduce the tracking error and to damp the resonant modes to increase the AFM scanning speed with improved image quality. The special feature of MPC is that its augmented integral action reduces the nonlinear behavior of the PZT scanner which, in turn, solves the tracking error problem and generate a tilting less image. It is also effective for non-minimum phase systems, like the AFM. In this control scheme a notch filter is used with MPC to damp the resonant modes and this reduces the mechanical vibration of the PZT scanner.

The rest of this paper is organized as follows: Section II presents the descriptions of the AFM and the experimental setup used in this work. Section III provides the modeling and identification of the system transfer functions. In Section IV, the control scheme for the AFM scanner is presented. Section V reflects the experimental results which illustrates the significant improvement in accuracy and imaging speed which can be achieved with the proposed control scheme. Finally, in Section VI, conclusions are drawn and suggestions regarding future work which could further improve control of the AFM are discussed.

II. EXPERIMENTAL SETUP

Fig. 3 shows the experimental setup which is used to implement the proposed control scheme at the University of New South Wales (UNSW), Canberra, Australia.

Setup consists of a NT-MDT Ntegra scanning probe microscope (SPM), which was configured to operate as an AFM. There are some important accessories of the AFM, such as signal access module (SAM), control electronics, noise isolator, and a computer. The other parts used for the control implementation are signal analyser (SA), DSP dSPACE 1103 board, and a high voltage amplifier (HVA).

The key component of an AFM positioning system is the PZT scanner. In this experiment a scanner NT-MDT z50313cl is used to perform 3D positioning in the AFM. It is a ‘scan by sample’ type scanner. It has a scanning range of \(100\mu m \times 100\mu m \times 12\mu m\), and resonant frequency in both \(x\) and \(y\) direction is approximately 900 Hz, and in the \(z\) direction is about 5 kHz. There are three capacitive position sensors, \(x\), \(y\), and \(z\) incorporated into the scanner apparatus to allow for direct measurements of tube displacements in the \(x\), \(y\), and \(z\) directions. The block diagram of experimental connection is shown in Fig. 4.

III. SYSTEM IDENTIFICATION

To simplify the control design, the AFM scanner is treated as a two single-input single-output (SISO) system. In this process the plant is identified by using a bandlimited random noise signal of amplitude 100 \(mV_{rms}\) within the frequency range of 10 Hz to 1100 Hz, using a dual channel HP35670A signal analyser. This signal is supplied to the HVA (with a gain of 15) as an input and the corresponding amplified voltage is supplied to the SAM of the AFM. From SAM there is a direct connection with the PZT scanner. The output displacement of the PZT scanner is taken from the capacitive position sensor as corresponding voltage. The sensor output is fed back to the SA to construct the following frequency response functions (FRFs):

\[
G_{d_x v_x}(s) = \frac{d_x(i\omega)}{v_x(i\omega)}
\]

(1)

and

\[
G_{d_y v_y}(s) = \frac{d_y(i\omega)}{v_y(i\omega)}
\]

(2)

where \(v_x\) and \(v_y\) are the voltage signals applied in the corresponding \(X\) and \(Y\) piezo, and \(d_x\) and \(d_y\) are the measured displacement from the corresponding capacitive position sensor. From this FRF using the prediction error method (PEM) best fit with the measured plot is chosen as described in references [17], [18]. The system behavior is characterized by processing the data from the identified model. The following transfer functions are found to be a good fit as shown in Fig. 5 and Fig. 6. It should be noted here that, there is about \(\pi\) radian phase shift between the inputs and outputs at low frequencies, both in the \(x\) and \(y\) sensor positions.

\[
G_{d_x v_x}(s) = \frac{-16.2s^2+3.108 \times 10^8s-9.791 \times 10^7}{s^3+295.4s^2+6.893 \times 10^4s+1.843 \times 10^7}
\]

(3)

and

\[
G_{d_y v_y}(s) = \frac{-14.81s^4+6.555 \times 10^4s^3-1.282 \times 10^8s^2+4.172 \times 10^7s-8.19 \times 10^3}{s^5+355.5s^4+1.547 \times 10^8s^3+4.832 \times 10^8s^2+5.835 \times 10^7s+1.604 \times 10^9}
\]

(4)
IV. CONTROLLER DESIGN

This section addresses the design of proposed MPC-Notch control scheme which is undertaken in this work. An MPC control technique is designed to reduce the tracking error problem of PZT scanner’s to improve the positioning of fast axis (x) and slow axis (y) and a notch filter is used for damping the resonant modes. The construction of the closed-loop system is shown in Fig. 7.

A. Design of Notch Filter

This section presents the design of a notch filter or vibration compensator. Since resonant modes are responsible for the mechanical vibration, we have introduced a notch filter in the proposed control scheme to suppress the vibration of PZT scanner. In this study, the following notch filter is added [16], [19]:

\[
M_i = \sum_{i=1}^{n} -k_i \frac{s^2 + 2\zeta_i \omega_i s}{s^2 + 2\zeta_i \omega_i s + \omega_i^2}
\]  

(5)

where \( i = 1, 2, \cdots, n \), \( \omega_i > 0 \) is the \( i \)th controller center frequency at the \( i \)th resonant peak of the plant, \( \zeta_i > 0 \) the damping factor, and \( k_i \) the notch filter gain of the corresponding mode. To suppress the first resonant mode we have chosen the following values, \( \omega_1 = 5600 \text{ rad/sec} \) and \( \zeta_1 = 0.06 \).

B. Design of MPC

The MPC scheme is employed to design a tracking controller in which the output tracks a reference triangular input. The basic structure of MPC is shown in Fig. 8. In MPC, the optimal control actions are found by optimizing the predicted plant behavior, while taking process constraints into account, which eliminate the possibility of variables exceeding their limits [20]. Model predictive control systems has designed based on a mathematical model of the plant [21]. The model to be used in the control system design is a state-space model. The plant system which is used for design of the controller can be expressed as the following state-space model

\[
x_m(k+1) = A_m x_m(k) + B_m u(k)
\]  

(6)

\[
y(k) = C_m x_m(k)
\]  

(7)

where \( A_m \), \( B_m \), and \( C_m \) are the discrete state-space plant model, extracted from the identified FRFs in Eqs. (3) and (4) and Eq. (5), \( u \) is the manipulated variable or input variable, \( y \) is the measured output, \( x_m \) is the state variable vector with dimension \( n \). In order to incorporate the integral action for disturbance rejection and tracking of a reference signal in the MPC algorithm, the plant can be augmented in the following way:

\[
\begin{bmatrix}
\Delta x_m(k+1) \\
y(k+1)
\end{bmatrix} = 
A 
\begin{bmatrix}
\Delta x_m(k) \\
y(k)
\end{bmatrix}
+ B \Delta u(k)
\]  

(8)

\[
y(k) = C 
\begin{bmatrix}
\Delta x_m(k) \\
y(k)
\end{bmatrix}
\]  

(9)
where:

\[
A = \begin{bmatrix} A_m & 0 \\ C_mA_m & I \end{bmatrix}; B = \begin{bmatrix} B_m \\ C_mB_m \end{bmatrix}; C = [0 \ I]
\]

\[
\Delta u(k) = u(k) - u(k-1)
\]

\[
\Delta x_m(k+1) = x_m(k+1) - x_m(k)
\]

\[
\Delta x_m(k) = x_m(k) - x_m(k-1)
\]

and \(A, B,\) and \(C\) are the augmented system matrices. The constrained MPC problem to be minimized is a quadratic one which is given by

\[
J = \sum_{m=1}^{N_p} Q(y(k+m|k)) - R_s(k+m))^2
\]

subject to linear inequality constraints on the system inputs:

\[
u_{\text{min}} \leq u(k+i-1) \leq u_{\text{max}}, \quad i = 1, \ldots, N_c \quad (11a)
\]

\[
\Delta u_{\text{min}} \leq \Delta u(k+i-1) \leq \Delta u_{\text{max}}, \quad i = 1, \ldots, N_c \quad (11b)
\]

where \(N_p\) is the prediction horizon, \(N_c\) is the control horizon, \(Q\) is the state weighting matrices, \(R\) is the control weighting, \(u_{\text{min}}\) and \(u_{\text{max}}\) are respectively the low and the high levels of the control action and \(\Delta u_{\text{min}}\) and \(\Delta u_{\text{max}}\) are respectively the low and the high levels of the control increments. The output sequence on \(N_p\), prediction horizon can be written as follows [21]:

\[
Y = Fx(k) + \Phi \Delta U
\]

in which,

\[
Y = [y(k+1|k), y(k+2|k), \ldots, y(k+N_p|k)]^T
\]

\[
\Delta U = [\Delta u(k), \Delta u(k+1), \ldots, \Delta u(k+N_c-1)]^T
\]

By considering the above equations, the constrained MPC problem can be expressed as a compact quadratic programming (QP) problem:

\[
\min \left( \frac{1}{2} \Delta U^T H \Delta U + \Delta U^T f \right)
\]

s.t. \( M \Delta U \leq \gamma \)

where:

\[
H = \Phi^T Q \Phi + R
\]

\[
f = \Phi^T Q F x(k+1|k) - \Phi^T Q R_s
\]

\( M \in \mathbb{R}^{m_c \times N_c} \) and \( \gamma \in \mathbb{R}^{N_c \times 1} \) are computed by using equation (11) and where \( m_c \) is the number of constraints and \( R_s \in \mathbb{R}^{N_p \times 1} \), is the reference signal.

The values of the different parameters of the MPC controller chosen to obtain desirable results from the experiment are as follows: \( N_p = 10, N_c = 1, \) sampling time, \( T_s = 1 \text{ms}, R = 0.05 \) and \( Q = I \).

V. EXPERIMENTAL RESULTS

A. Frequency domain performance of the proposed controller

The performance of the MPC-Notch control scheme is evaluated first by measuring the closed-loop frequency responses of the system by using the SA. In Fig. 9 and Fig. 10, the measured closed-loop frequency responses are plotted along with the open-loop frequency responses of the \( X \) and \( Y \) piezo displacement respectively. From these figures, it can be observed that the closed-loop system bandwidth for both \( x \) axis and \( y \) axis is approximately 400 Hz. For both cases also having more than 20 dB damping in the closed-loop system which in turns reduces the vibration significantly.

It should be noted here that with the current experimental setup, it was not possible to measure the closed-loop frequency responses of the AFM scanner with well-tuned PI controller that is built into the AFM.
Fig. 10. Comparison of measured open-loop and closed-loop frequency response of the Y piezo.

B. Experimental tracking performance of the proposed controller

To understand the improvement achieved in the lateral positioning of the scanner by implementing the proposed controller is shown in the Fig. 11. In this experiment MPC-Notch control scheme is applied to the x axis of the PZT for tracking a reference triangular input signal, which is set at 5.21 Hz. The minimization of the cross coupling effect is shown in Fig. 11(b).

Fig. 11. Closed-loop and reference signal tracking performance (left) and cross-coupling properties of the scanner (right) [red (closed-loop) and blue (open-loop)].

C. Imaging performance of the proposed controller

Having enhanced the lateral positioning of the PZT scanner, we have then focused on the analysis of the overall improvement in imaging capability of the AFM. By using the existing NT-MDT AFM scanning NOVA software, scanning speeds above 10 Hz can only be set to frequencies of 10.42 Hz, 31.25 Hz, 62.50 Hz, and 125 Hz. During the imaging the AFM is operated in constant force mode by using a micro-cantilever. To show the imaging performance of the proposed control scheme over open-loop is shown in Fig. 12. Figs. 13 to 16 illustrate the results obtained by implementing the MPC-Notch control and present a significant difference with the image taken by the existing PI controller. Each of these images was obtained by scanning a NT-MDT TGQ1 grating reference sample by using NT-MDT CSG01 micro-cantilever.

Fig. 12. Scanned images at 10.42 Hz (a) open-loop and (b) using the proposed controller.

Fig. 13. 10.42 Hz scanned images using the AFM PI controller (a) 2D-image, (c) 3D-image and using the proposed controller (b) 2D-image, (d) 3D-image.

Fig. 14. 31.25 Hz scanned images using the AFM PI controller (a) 2D-image, (c) 3D-image and using the proposed controller (b) 2D-image, (d) 3D-image.
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REFERENCES


VI. CONCLUSION AND FUTURE WORK

In this paper, the proposed control scheme for fast scanning by an AFM was implemented. A notch filter was used to remove the major resonances of the system and the MPC controller retuned. The experimental results showed that the scanning performance of the AFM was radically improved by implementing the proposed MPC-Notch control scheme. From a comparison of the scanned images obtained using the proposed controller and existing PI controller, it could be seen that, up to a 125 Hz scanning speed, those from the former were far better than those from the latter.

While this experiment focused on the lateral positioning of the AFM scanner, future research will involve its vertical positioning to achieve advanced resolution images from faster scans.

Fig. 15. 62.50 Hz scanned images using the AFM PI controller (a) 2D-image, (c) 3D-image and using the proposed controller (b) 2D-image, (d) 3D-image.

Fig. 16. 125 Hz scanned images using the AFM PI controller (a) 2D-image, (c) 3D-image and using the proposed controller (b) 2D-image, (d) 3D-image.