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Haptics Enabled Offline AFM Image Analysis

Bhatti A., Nahavandi S. and Hossny M.

Abstract—Current advancements in nanotechnology are dependent on the capabilities that can enable nano-scientists to extend their eyes and hands into the nano-world. For this purpose, a haptics (devices capable of recreating tactile or force sensations) based system for AFM (Atomic Force Microscope) is proposed. The system enables the nano-scientists to touch and feel the sample surfaces, viewed through AFM, in order to provide them with better understanding of the physical properties of the surface, such as roughness, stiffness and shape of molecular architecture. At this stage, the proposed work uses offline images produced using AFM and perform image analysis to create virtual surfaces suitable for haptics force analysis. The research work is in the process of extension from offline to online process where interaction will be done directly on the material surface for realistic analysis.

Keywords—Haptics, AFM, force feedback, image analysis.

I. INTRODUCTION

RECENT advances in nanotechnology have enabled widespread opportunities to investigate and manipulate materials at nanometer level. Nano-manipulation has attracted a lot of research in recent years and a number of manipulation techniques has been proposed [1], [2], [3], however are very unintuitive. Most of these techniques are based on *Atomic Force Microscope* (AFM) [4] due to its working principle, which makes use of the concept of physically running a metallic pointer (cantilever) with $0.027nm$ to $0.15\ nm$ resolution over the sample surface. Technologies, such as atomic force microscope, are capable of enabling the scientists with visualization of the materials up to nano-meter level with some capabilities of nano-manipulation. Atomic Force microscopy (AFM) [14] has been proven to be a powerful technique to study sample surfaces down to the nanometer scale. Not only can it characterize sample surfaces, it can also change the sample surface through manipulation. Nano-manipulation using AFM has attracted much attention among researchers in recent years and various kinds of manipulation schemes have been developed in last decade [15], [16], [17], [18]. The main problem of these manipulation schemes is the lack of real-time visual feedback. Each operation has to be verified by another new image scan before the next operation. Obviously, this *scan design manipulation scan* cycle is time consuming and makes mass production impossible. The positional movement of the pointer is then translated into a graphical surface image for visualization. Furthermore, the pointer can be used to manipulate sample surface at nano-meter level by pressing the surface with the cantilever tip.

However, in all existing nano-manipulation techniques an intuitive direct user interaction with the sample material is somewhat limited [5]. Generally, the user is provided with a 3D image of sample surfaces and the analysis of the surface is performed using image processing based software [6]. In addition, nano-manipulations, such as done by atomic force microscope, require offline analysis of the material and information, which is then passed to the atomic force microscope to manipulate the surface of the material if required. These limitations involved in the study and manipulation of materials at nanometer level reflects a wide gap that needs to be bridged [5] to provide the user with better understanding of the materials and more intuitive ways to manipulate.

Moreover, it is psychologically and medically proven that the sense of touch is one of the most important and intuitive ways of understanding different physical properties of the materials. However, achieving sense of touch directly at nano-scale level is out of the reach of humans due to the limitations of human sensors. Therefore, to provide an intuitive and comprehensive platform for investigation, study and manipulation of materials at nano-meter level, we propose a haptics technology (devices capable of recreating tactile or force sensations within the virtual world) [7] based visualization system for Atomic Force Microscope. This system will enable the user, along with the visualization, to touch and feel the sample surfaces, viewed through atomic force microscope, for better understanding of the physical properties such as roughness, stiffness and shape of molecular architecture.

In the proposed project, a haptics technology [8], [9] based force sensation system for Atomic force microscope is developed. This system will enable the user to feel the physical properties of the sample surface. The aims to achieve the aforementioned functionalities can be subdivided into four sub-aims:

1 Accurate estimation of the cantilever deflection with respect to the sample surface during sample surface scanning
2 Estimation of the force components encountered by the cantilever tip by establishment a closed form relationship between cantilever deflection and the force exerted on the tip during scanning
3 Establishment of a relationship between the force exerted on the cantilever tip (established in 2) and the force vectors required for the haptics interface to provide force sensations
4 Design of the haptics system to reflect the estimated forces, as aforementioned, during offline image analysis

The haptics based force sensation system enable the users to touch the sample surfaces and feel the accurate physical properties of the sample. The proposed system generates new opportunities to study and investigate materials in a more

Bhatti A., Nahavandi S. and Hossny M.
are with the center for Intelligent Systems Research, Deakin University, Vic 3217 Australia
Email: asimbh@ieee.org, nahavand and mhossny @deakin.edu.au

intuitive and understandable way. Furthermore, as the physical properties and sensation that are reflected by the haptics interface are based on the accurate estimation of the forces acting on the cantilever tip therefore, the information can be further used for modeling of the materials in order to study its behavior in different environmental conditions.

Generally the study and investigation of the sample properties and manipulation, at nanometer level, is solely based on the visual information. In other words, an intuitive interaction of the scientists with the material at this nano scale is missing. That is the capability of direct interaction where user can feel the physical properties of the material such as stiffness, friction, roughness, etc. at nano-scale level. In this project, an innovative system is developed with the combined functionality and features of atomic force microscope [4] and the haptics technology [8], [9]. Atomic Force Microscope has proven to be one of the most powerful and effective tools to study and manipulate samples at the nano-scale level whereas the haptics technology has proven to be one of the most intuitive ways of providing information by recreating tactile or force sensations within the virtual world.

The proposed project will lead to the development of an innovative force sensation system for atomic force microscope enabling the user to visualize the magnified sample surface produced by microscope and will be able to touch and feel the accurate physical properties of the material such as roughness, stiffness, friction and molecular architecture of the sample surface. For this purpose, an analytical relationship, between the deflection of cantilever tip (scanning probe) of atomic force microscope [10], [11] and the forces exerted on the cantilever tip [12], will be established. This relationship will generate force vectors that will be used to provide touch sensation using haptics devices. The forces are required to be sensed within the range of $0.1\mu N$ to $200\mu N$ [5]. Therefore, it is very important and required to establish a comprehensive relationship between the cantilever deflection and force exerted on and by the cantilever. Consequently, the forces exerted through the cantilever tip, as shown in Figure 1, required to be up-scaled appropriately to create a proper force sensation to the user.

II. INTERACTIVE FORCES ESTIMATION

To perform offline haptic analysis of the sample surfaces, created through AFM, the real forces exerted on the cantilever tip, during scanning needs, to be estimated. These estimated forces will then be registered along with the scanned image to be reflected during the haptics image analysis. This will provide a realistic understanding of the material properties in terms of normal, lateral and friction forces while analyzing AFM image offline. The forces exerted on the AFM tip can generally be expressed by two force components, i.e. normal and lateral [13] as shown in Figure 1. The normal force component F_N can be expressed by using a simple spring model as

$$F_N = k_N \ \delta_Z \tag{1}$$

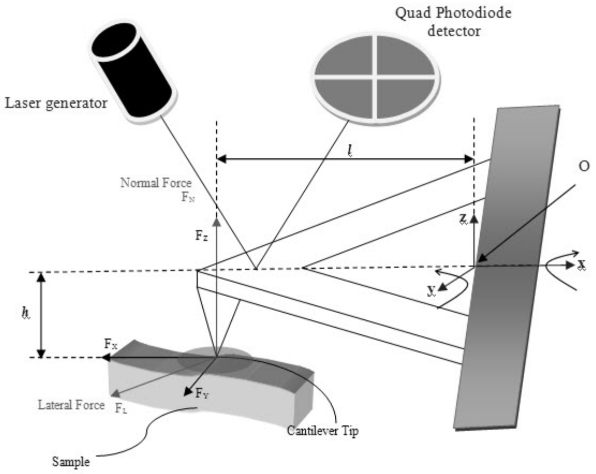

Fig. 1. AFM cantilever tip force model

where δ_Z defines the deflection whereas k_N is the spring constant and can be defined in terms of Young's modulus as

$$k_N = \frac{Ewt^3}{4L^3} \tag{2}$$

where E is Young's modulus.

The cartesian force components of F_N can be expressed, explicitly, as (F_X, F_Y, F_Z). While applied, these force generate respective torque components (τ_X, τ_Y, τ_Z) at point O as shown in Figure 1 and can be expressed, in terms of (F_X, F_Y, F_Z) as

$$\begin{cases} \tau_X = F_Y \ h \\ \tau_Y = -F_Z \ l - F_X \ h \\ \tau_Z = F_Y \ l \end{cases} \tag{3}$$

Where h and l are dimensional parameters defining the height and the length of the cantilever as shown in Figure 1. Where τ_X causes the cantilever end to twist at θ_X along X axis, τ_Y causes the cantilever to bend δ_Z in Z direction whereas τ_Z causes the cantilever to bend δ_Y in Y direction. Based on the quad photodiode configuration [13], θ_X and δ_Z can be obtained as

$$\theta_X = K_L \ P_L \tag{4}$$

$$\delta_Z = K_N \ P_N \tag{5}$$

Where P_L and P_N are lateral and normal components of the quad photodiode output signal, respectively, whereas K_L and K_N are respective system constants. Considering F_Z and F_X cause τ_Y, F_N along the Z axis can be defined as

$$F_N = F_Z + \frac{h}{l} F_X \tag{6}$$

From expression 1 and 4 we have

$$F_N = k_N \ K_N \ P_N \tag{7}$$

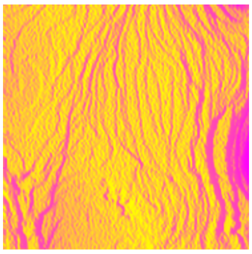

Fig. 2. An example of an Image produced by AFM

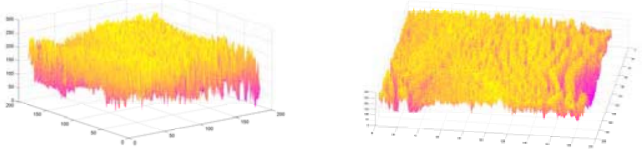

Fig. 3. Surface created using filter image from Figure 2

Furthermore, with the known motion direction of the cantilever tip the lateral force can be calculated as an opposite measure to the direction. For example if the motion direction has an angle ϕ with respect to the X axis then the later force can be expressed as

$$F_L = \frac{F_Y}{sin\phi} \tag{8}$$

whereas

$$F_Y = \frac{k_l}{h}\theta_X = \frac{k_L\ K_L}{h}P_L \tag{9}$$

k_l in expression (9) defines the torsion constant of the cantilever. Similarly F_X in terms of F_Y can be defined as

$$F_X = F_Y\ tan\phi \tag{10}$$

In general all the cartesian force components exerted on the cantilever tip can be estimated using normal and lateral signal information as

$$\begin{cases} F_X = -F_Y\ ctan\phi \\ F_Y = \frac{k_l\ K_L}{h}\ P_L \\ F_Z = kK_N P_N - \frac{h}{l}F_X \end{cases} \tag{11}$$

Finally to provide force sensation to the user through the haptics device, force components calculated in expression (11) are multiplied with the cantilever frame rotational matrix as

$$F_h x = R^{-1}F^T \tag{12}$$

Where $F_h x$ defines the sensation force of the haptics devices whereas F defines the forces exerted on the cantilever tip comprised of $[F_X, F_Y, F_Z]$. Where R defines the relationship between AFM and the cantilever frame and can be expressed as

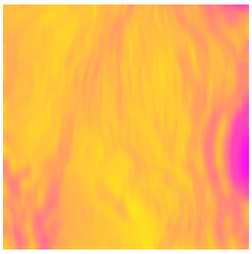

Fig. 4. Filtered version of the Image from Figure 2 using circular averaging filter

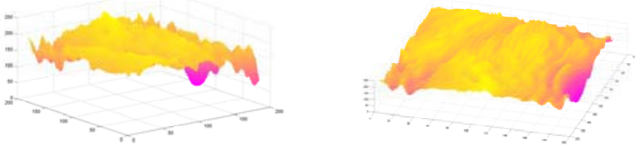

Fig. 5. Surface created using filter image from Figure 2

$$R = \begin{bmatrix} -cos\ \psi & sin\ \psi & 0 \\ -sin\ \psi & -cos\ \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

In this particular presentation only the normal force components are considered and are registered with the virtual surface produced from images to provide proper stiffness factor for the haptics interface. Considering, the overall process presented is offline and the images are filtered to produce relatively smoother representation (presented in the next section III) therefore lateral forces' contribution is irrelevant. However the overall force representation from expression 12 is required for online process which is the ultimate goal of the research work and will be presented in the future.

III. IMAGE SMOOTHING FOR HAPTICS ANALYSIS

Images considered for this analysis are produced by AFM for different materials. Due to the presence of noise introduced during the AFM scanning process the images are required to be filtered. Filtering is also important to remove sharp discontinuities within the image to provide a smoother force sensation during image analysis using haptics device. Number of simple filtering techniques have been employed in this process including average, circular averaging, gaussian and motion filters.

One raw image produced by AFM is shown in Figure 2 along with the produced relevant surface map, shown in Figure 3. It is quite apparent that produced surface map is very discontinuous and is not suitable for haptics force rendering. Furthermore haptics virtual surface generated through this unfiltered image will produce very unrealistic force sensation consequently providing no extra information in reference to the surface properties during image analysis. To address the noise and discontinuity issues incorporated into the AFM produced

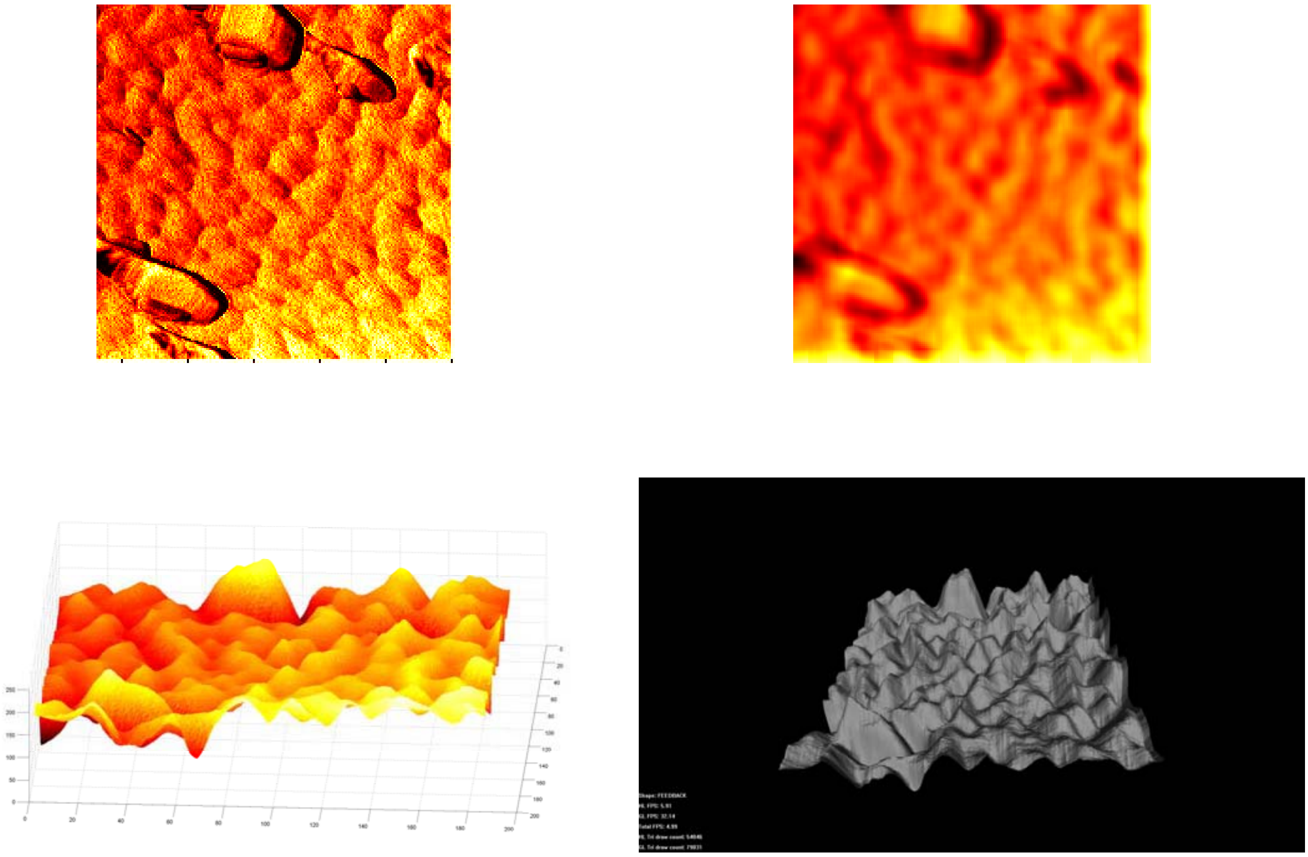

Fig. 6. top-left: Raw AFM image of the scanned sample, top-right: Filtered version of raw Image (left), Bottom-left: Rendered surface of the filtered image (top-right), Bottom-right: Generated virtual Haptics surface

raw images, different filtering techniques are incorporated. An example of the smoothing performed using circular average filter is shown in figures 4. The respective surface map can be visualized by Figure 5. It is obvious, the rendered surface is relatively smoother and is better candidate for rendering as a virtual surface for haptics analysis. It is planned to extend this filtering process to multi-resolution and wavelets and multiwavelets scale-space representation based image smoothing [19]. The produced image surface is then converted to 3D .OBJ object format to create haptics surface for further analysis.

IV. HAPTICS SURFACE RENDERING

In computer graphics, the surfaces are rendered using a mesh of triangles. The image surfaces produced in section III are converted to 3D .OBJ object format defining the vertex indices and the respective faces. The cartesian force components estimated earlier, in section II, are then rendered with the vertices to provide realistic force sensation. The pre-rendered forces generate realistic haptics interaction, similar to the normal forces that has actually been exerted on the AFM tip while scanning. Some force magnitude scaling has been performed to create a sensible sensation as the sensed forces are within the range of $[0.1 \quad 200]\mu N$ as well as due to the haptics devices' capabilities. For this particular research work SensAble's Phantom® Omni which is capable of reflecting approximately $3N$ peak static and approximately $0.3N$ peak continuous force.

During the image analysis using haptics device, the user scans the haptic pointer (representing AFM tip) of the haptics device over the virtual surface. During collision of the haptic pointer with the virtual surface already rendered forces, pre-registered to the colliding vertices, are reflected through the haptics devices providing the physical properties of the material surface such as surface roughness, material stiffness, etc.

Examples of the presented process are shown in Figures 6 and 7. Both images belong to Aluminium alloy samples. In both images, even though, surface properties are reasonably apparent however does not provide much information about the gradient of the discontinuities, friction, stiffness and roughness of the material surface. The bottom right image in both Figures 6 and 7 shows a virtual haptic surface generated from the processed images shown at the top of the same figures. The rendered haptic surface posses the properties of roughness, stiffness, friction based on the pre-registered forces estimated earlier from the AFM cantilever tip. It is believed that consideration of sense of touch, highlighting extra features as aforementioned (discontinuities, friction, stiffness and roughness) along with the visual information would help

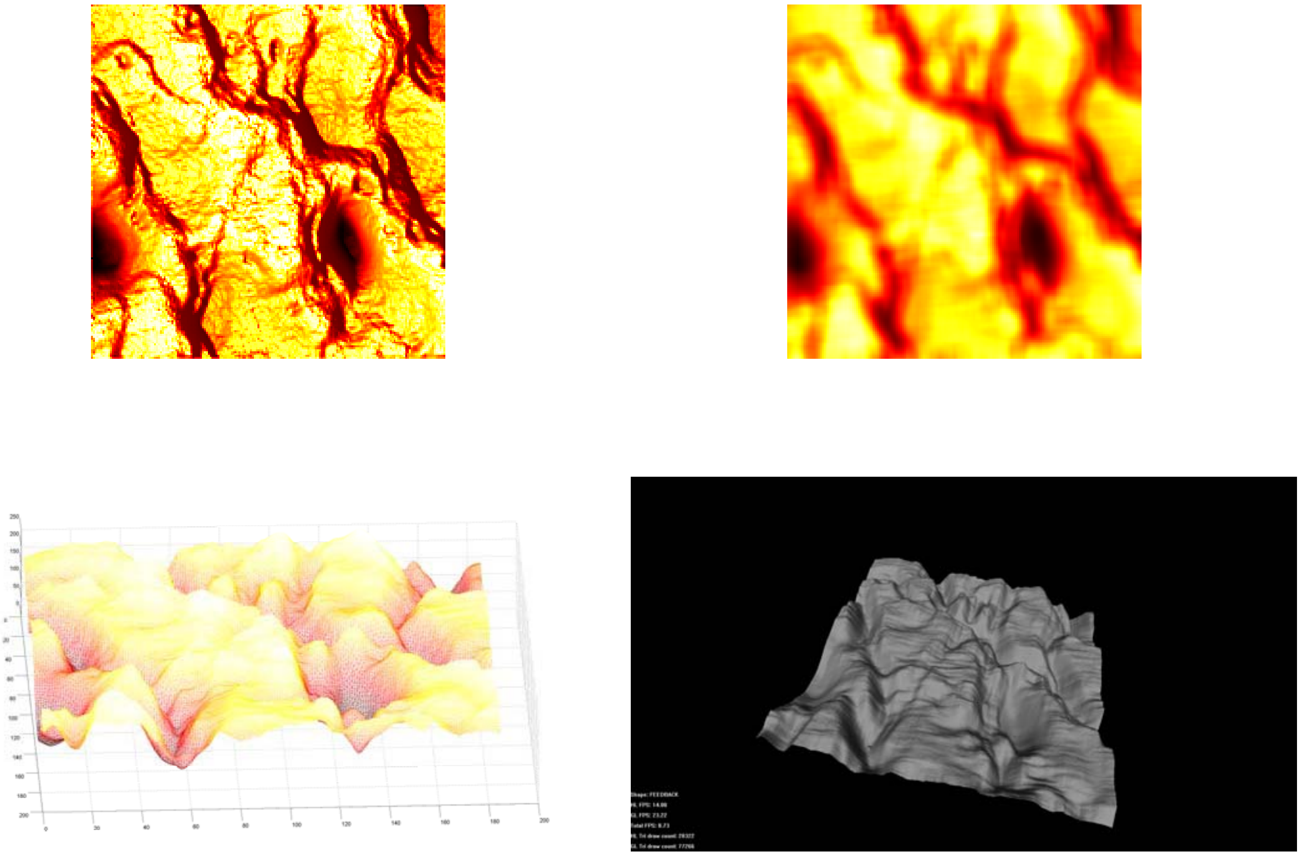

Fig. 7. top-left: Raw AFM image of the scanned sample, top-right: Filtered version of raw Image (left), Bottom-left: Rendered surface of the filtered image (top-right), Bottom-right: Generated virtual Haptics surface

scientists to understand the materials better.

V. CONCLUSION

In nano-science related studies, an intuitive direct interaction with the sample materials is somewhat limited due to the size constraints. Generally, the user is provided with a 3D image of sample surfaces and the analysis of the surface is performed using image processing based software. These limitations involved in the study at nanometer level reflects a wide gap that needs to be bridged to provide the user with better understanding of the materials and more intuitive ways of interaction.

To address the aforementioned gap an attempt has been made to enable nano-scientists to directly interact with the nano-materials using haptics technology. In this respect, a haptics force sensation system has been proposed that makes use of the image filtering techniques to create smooth virtual surfaces of the AFM images. the proposed system enables the users to touch the sample surfaces and feel the accurate physical properties of the sample.

The system will generate new opportunities to study and investigate materials in a more intuitive and understandable way. Furthermore, as the physical properties and sensation that will be reflected by the haptics interface are based on the accurate estimation of the forces acting on the cantilever tip therefore, the information can be further used for modeling of the materials in order to further study its behavior in different environmental conditions.

In addition, the outcome of the project will establish grounds for further development of nano-manipulation, where the user will be able to manipulate the material at nanometer level with an intuitive control of cantilever tip through haptics device. The forces imposed on the cantilever tip are required to be constrained with in the range of $0.1\mu N$ to $200\mu N$. Considering this fragility of the manipulation the real-time force feedback becomes an absolute necessity. Without force sensation, unknowingly an excessive force applied to a nano-object may cause a significant degree of AFM cantilever damage or object deformation consequently destroying the nano-object.

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