

# Controller Design for Z Axis Movement of STM Using SPM Control Software

Neena Tom, Rini Jones S. B

*Abstract Scanning probe microscopy is a branch of microscopy that forms images of surfaces using a physical probe. This paper is devoted to the control system design for high performance scanning tunneling microscope (STM). The distance between tip and sample should be kept constant at every point of sample for better scanning results. Note that many samples have roughness, curvature and tilt that deviate from a flat plane. So it is necessary to move the probe in z-axis to maintain the height of probe from sample constant. But a sudden change in probe position can damage the probe. SPM feedback loops usually employ a proportional-integral (PI) controller to control the vertical movement of tip (z-direction). Our aim is to implement an accurate tuning algorithm that can find PI values that gradually change the position of the probe for higher safety and precision. Moreover, better sample topography image can be obtained after auto-tuning the control gains during different scanning speed. The square wave is given as input to the PI controller which represents the sudden change of surface that cause damage to the system, and the output should be triangular wave in nanometer range by proper tuning of PI controller. Triangular wave represents the tip being moved by the controller in z direction at the time represented by the square wave input.*

*Index Terms—Scanning tunneling microscope, feedback loops, PI controller, tuning algorithm.*

## I. INTRODUCTION

Scanning probe microscopy involves controlling the movement of a sharp tip in close proximity to or in contact with a surface with sub nanometer accuracy. High resolution image can be accrued by raster scanning the tip over a surface while continuously monitoring the interaction between tip and surface. Scanning typically occurs in an "x-y" plane that is at least generally parallel to the surface of the sample, and the vertical movement occurs in the "z" direction that is perpendicular to the x-y plane. Note that many samples have roughness, curvature and tilt that deviate from a flat plane. The distance between tip and sample should be kept constant at every point of sample for better scanning results. So it is necessary to move the probe in z-axis to maintain the height of probe from sample constant. But a sudden change in probe position can damage the probe. SPM feedback loops usually employ a proportional-integral (PI) controller to control the vertical movement of tip (z-direction). This paper is devoted to the control system design for high performance scanning tunneling microscope (STM). The aim is to implement a tuning algorithm that can find PI values that gradually change the position of the probe for higher safety and precision.

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The square wave input that represents a sudden change of surface is given to PI controller and triangular wave of same time period in nanometer range is obtained. Triangular wave represents the tip being moved by the controller in z direction at the time represented by the square wave input. In this paper, we employ and implement a program to automate the tuning procedure for STM PI controller. Moreover, better sample topography image can be obtained after auto-tuning the control gains during different scanning speed. Automation of PI controller with SPM control software is done by using C++ language in Visual Studio 2008 Platform.

## II. SYSTEM OVERVIEW

Scanning tunneling microscope (STM) is an important tool in obtaining images of a material surface in atomic level. It was invented by G.Binnig and H.Rohrer in the beginning of 1980s and now, it has become an important instrument in surface science laboratories. Fig1 shows its essential components. The STM is based on the concept of quantum tunneling. When a bias (voltage difference) is applied between tip and sample, electrons are tunnel through the vacuum between them. The resulting tunneling current is a function of tip position, applied voltage, and the local density of states (LDOS) of the sample. The scanning waveforms, applying on the x and y piezo directions, make the tip raster scan on the sample surface. A bias voltage is applied between the sample and the tip to induce a tunneling current. The z piezo is controlled by a feedback system to maintain the tunneling current constant. The voltage on the z piezo represents the local height of the topography. To ensure stable operation vibration isolation is essential.

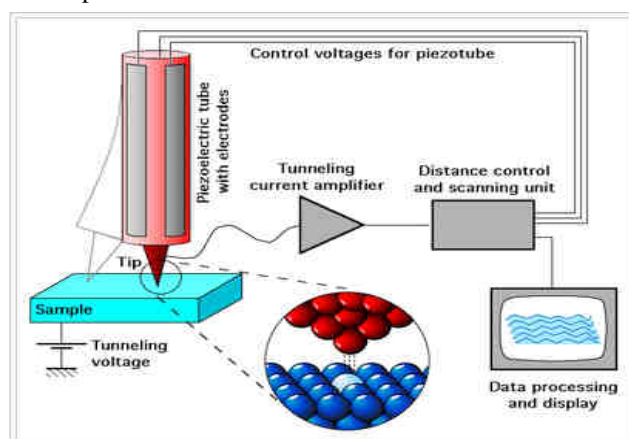


Fig. 1. Basic diagram of STM

The most widely used convention of the polarity of bias voltage is that the tip is virtually grounded. The bias voltage  $V$  is the sample voltage. If  $V > 0$ , the electrons are tunneling from the occupied states of the tip into the empty states of the sample. If  $V < 0$ , the electrons are tunneling from the occupied states of the sample into the empty states of the tip.

The tunneling current is converted to a voltage by the current amplifier, which is then compared with a reference value. The difference is amplified to drive the z piezo.

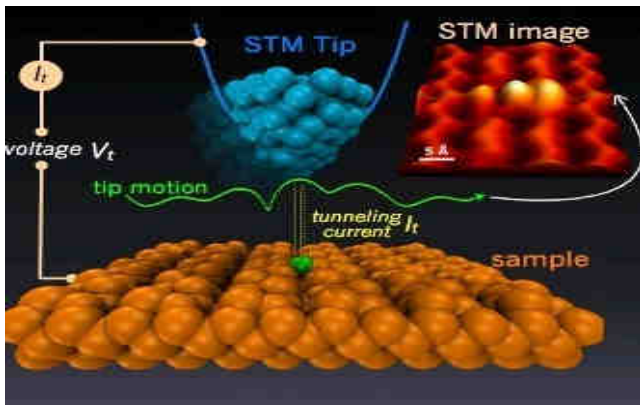


Fig. 2. Scanning of a sample using STM

The phase of the amplifier is chosen to provide a negative feedback. If the absolute value of the tunneling current is larger than the reference value, then the voltage applied to the z piezo tends to withdraw the tip from the sample surface, and vice versa. Therefore, an equilibrium z position is established. As the tip scans over the xy plane, a two-dimensional array of equilibrium z positions, representing a contour plot of the equal tunneling-current surface, is obtained, displayed, and stored in the computer memory.

Tunneling current depends on

- the tip surface distance d
- the voltage V (Bias)
- the height of the barrier  $\Phi$

The current depends exponentially on the distance d.

$$I(d) = \text{constant} * eV \exp(-2 \frac{\sqrt{2m\Phi}}{h} d)$$

The following graph shows the relation between tunneling current and distance between tip and sample.

- $\phi$  : the work function(energy barrier),
- e : electron charge.
- m : electron mass
- h : planck's constant
- v : applied voltage
- d : tip sample distance

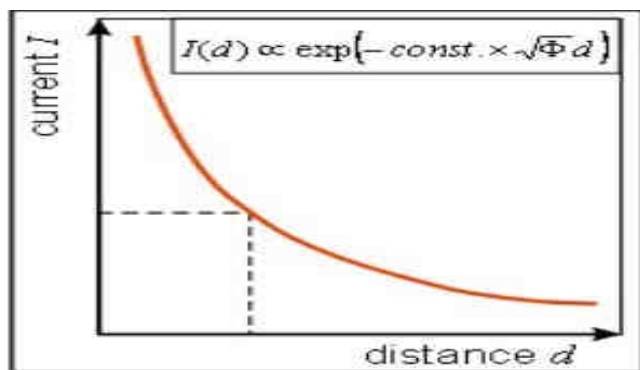


Fig. 3: Relation between tunneling current and distance

### III. PROPOSED SYSTEM

Many samples have roughness, curvature and tilt that deviate from a flat plane .In STM the distance between tip and sample should be kept constant. So it is necessary to move the probe in z-axis to maintain the height of probe from sample constant.

But a sudden change in probe position can damage the probe. STM feedback loops (proportional-integral (PI) controller) to control the z direction movement of tip. Here we are implementing a tuning algorithm that can find PI values that gradually change the position of the probe for higher safety and precision. Automation of tuning algorithm for the PI controller In STM is also implemented. Automation of PI controller with SPM control software is done by using C++ language in Visual Studio 2008 Platform. Here the input from SPM controller is a square wave that represents the distance between probe and sample in nano Ampere. The square wave input represents the sudden change of surface. Input represents a change in current (in nA) with square wave that represents the distance between probe and sample.

### IV. PROPOSED SYSTEM BLOCK DIAGRAM

#### 4.1. Hardware space

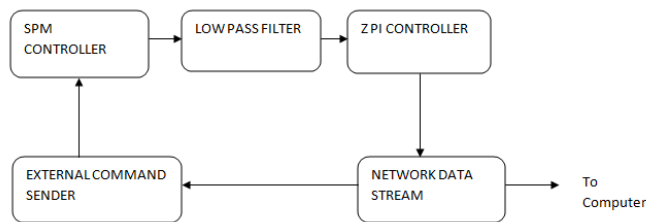


Fig. 4. Hardware space of proposed system

#### 4.1.1. Description

The data from the SPM controller is given to the ZPI controller through low pass filter. The Feedback Loop is a Proportional-Integral (PI) controller that allows independent settings of the Proportional and Integral feedback parameters. The Feedback Loop parameters carry the standard SI units Network data stream is used to convert output of PI controller to byte stream in order to read by computer for further processing. An external command receiver used to receive command from computer. For eg: we can send command from program code to increase integral gain by a factor.

#### 4.2. Software part

The software part is done by using C++ language in Visual Studio 2008 platform.

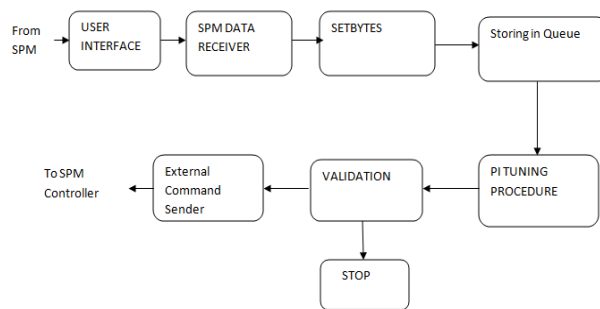


Fig. 5. Software part of proposed system

#### 4.2.1 Description

The User can start the application using Start button. Then the data from hardware is converted to byte stream using Network Data Stream. This byte stream is SPM data receiver through socket programming. Setbytes is a function that converts the received byte stream in to structure, where each packet of data contains time period, amplitude, PI data etc. These packets are stored in a queue and PI tuning procedure is

running here. After validation, if the desired output is not obtained, PI values are increased gradually and given to SPM controller.

## V. PI CONTROLLER

STM imaging relies on feedback loops to maintain a constant interaction between the tip and the sample. For reliable STM operation and analysis, the characteristics of such feedback loops must be considered. STM feedback loops usually employ a proportional-integral (PI) controller. The combination of proportional and integral terms is important to increase the speed of the response and also to eliminate the steady state error.

The proportional and integral terms is given by:

$$u(t) = K_p e(t) + K_i \int e(t) dt$$

## VI. TUNING OF PI CONTROLLER

Tuning a control loop is the adjustment of its control parameters (proportional band/gain, integral gain/reset) to the optimum values for the desired control response. Stability is a basic requirement, but beyond that, different systems have different behavior. Here we are using Good Gain Method for tuning of PI controller.

### Good Gain Method

This method is introduced by Finn Haugen. The Good Gain method is a simple method which seems to give good results on the lab and on simulators. The method is based on experiments on a real or simulated control system. Good gain method does not require the control loop to get into oscillations during the tuning. It also gives better stability. The steps are given below.

1. Bring the process to or close to the normal or specified operation point.
2. Set the set point of the system.
3. Apply the input signal (square wave) to the system.
4. Ensure that the controller is a P controller with  $K_p = 0$  (set  $T_i = \infty$ ).
5. Increase  $K_p$  until the control loop gets satisfactory stability. The gain value is denoted as  $K_{PGG}$ .
6. Change the  $K_i$  value from zero.
7. Reduce  $K_p$  to 80% of the original value to improve the stability.
8.  $K_p = 0.8K_{PGG}$
9. Increase  $K_i$  until the response in the measurement signal becomes the expected signal(perfect triangular wave)
10.  $K_i = 0.66kp/T_u$
11. Check the stability of the control system with the above controller settings by applying a step change of the setpoint. If the stability is poor, try reducing the controller gain in combination with increasing the integral time.

## VII. IMPLEMENTATION DETAILS

### i. SPM Control Software

This Software uses a powerful Advanced Flow Programming Language, AFPL and has several distinct components that enable separate aspects of SPM work:

## Hardware Space of SPM Control Software

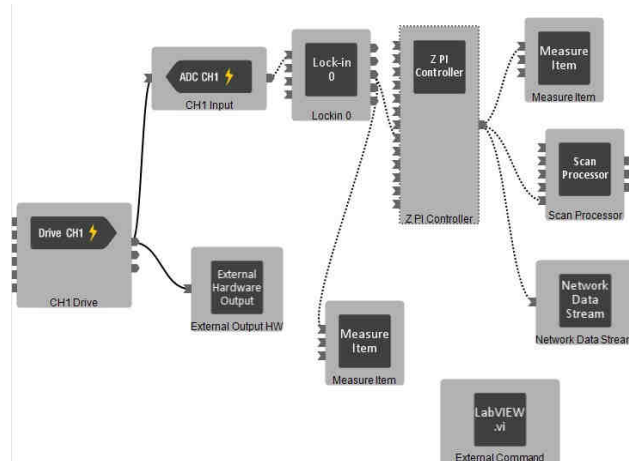


Fig. 6. Hardware space of SPM control software

### ii. AFPL Element Details

Channel 1 Drive is a simple icon with only one output pin. This output pin represents the bias output that is connected to the sample in the STM through the Channel1 Drive. The main function of Lock-in Amplifier is to act as low pass filter and spectroscopic measurements. The Feedback Loop is a Proportional-Integral (PI) controller that allows independent settings of the Proportional and Integral feedback parameters. The Feedback Loop parameters carry the standard SI units. The units of the Proportional Gain are Output Units/Input Units. In the case of STM, this would be Meters/Amp (or nm/nA). The units of the Integral Gain are Output Units/Input Units/second. Again in the case of STM, this would be Meters/Amp-Seconds (or nm/nA-S). The Z PI Feedback loop controls the Z position of the scanning probe. The signal output of the Lock in Amplifier is connected to the input pin of the ZPI loop. The output pin of the ZPI loop is connected to the signal pin of measure item, which will send the Topography channel to the PC over the Ethernet connection. The output pin of the ZPI loop is also connected to the Z input of the Scan Processor. The Measure Item is the component that enables the data channels in the Controller. The Scan Processor is a firmware component that controls the motion of the probe during imaging. Network data stream is used to convert output of PI controller to byte stream in order to read by computer for further processing. LabVIEW.in is an external command receiver used to receive command from computer. For eg: we can send command from program code to increase integral gain by a factor. Then the External Command Receiver will increase the  $K_i$  value of ZPI by a given factor.

## VIII. INPUT TO THE PI CONTROLLER

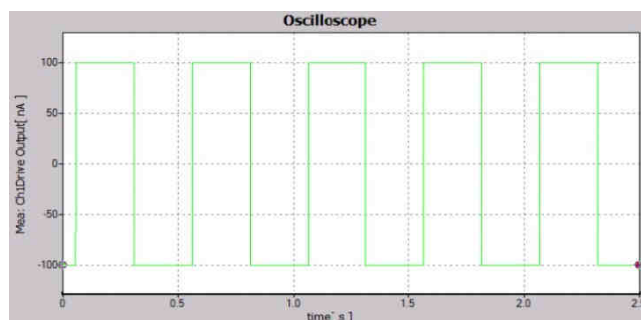
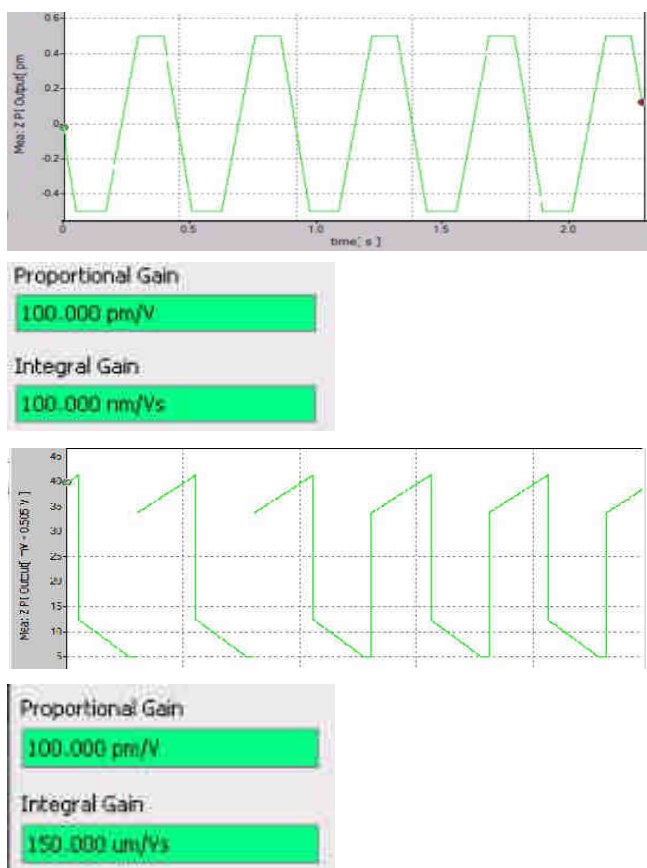


Fig. 7. Input to the PI controller

Input represents a change in current (in nA) with square wave that represents the distance between probe and sample. The amplitude of square wave represents the change in distance and the time period represents the responsiveness required for the PI controller. That is the time in which the z should respond and reach desired value.

**IX. EXPERIMENTAL RESULTS**

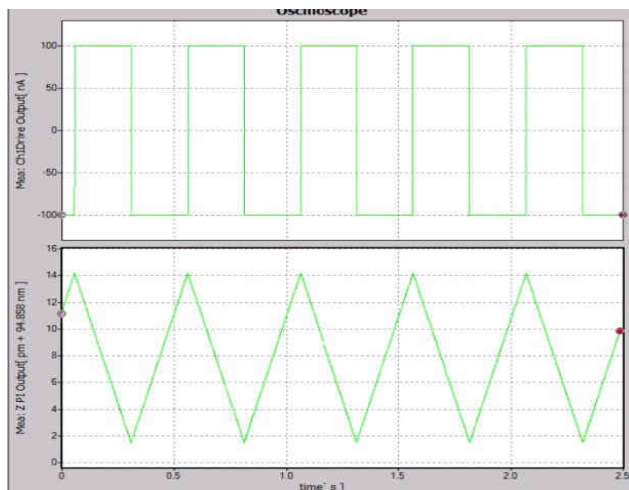
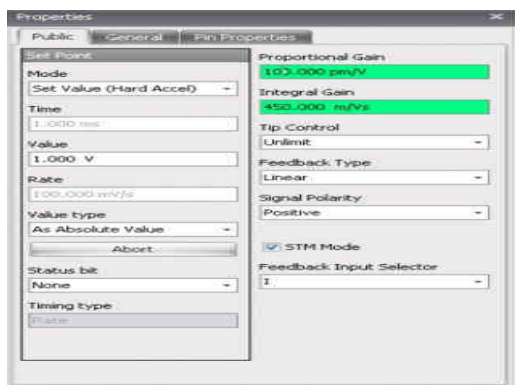
The square wave is given to the PI controller and triangular wave in nm range is obtained by proper tuning of PI controller. Triangular wave represents the tip being moved by the controller in z direction at the time represented by the square wave input. If the PI controller is not tuned with the right set of parameters, the z output will either not change or change too fast. Results with Ziegler –Nichols tuning and other methods given below.



**Fig. 8. Comparison with Ziegler –Nichols tuning methods**

**X. RESULT**

PI control panel



**Fig. 10. Result showing input and output.**

**XI. CONCLUSION**

This paper has demonstrated a practical tuning method for scanning tunneling microscopy. In this paper, we employ and implement a program to automate the tuning procedure for STM PI controller, for gradually changing the probe position, according to distance between sample and tip. Moreover, better sample topography image can be obtained after auto-tuning the control gains during different scanning speed. Here we are giving input as a change in current (in nA) with square wave that represents the distance between probe and sample. The amplitude of square wave represents the change in distance and the time period represents the responsiveness required of the PI controller. That is the time in which the z should respond and reach the desired height. If the PI controller is not tuned with the right set of parameters, the z output will either not change or change too fast. We implement a tuning algorithm to gradually change the probe position and reach to the desired height at the given time period. The square wave is given to the PI controller and triangular wave in nm range is obtained by proper tuning of PI controller. Triangular wave represents the tip being moved by the controller in z direction at the time represented by the square wave input. The square wave and triangular wave can be verified using oscilloscope.

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