Instrumentation and Algorithms for the Sonification of Scanning Probe Microscopy Output

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***Abstract*—The present work reports on the development of scientific instrumentation in scanning probe microscopy (SPM), a field of wide application and versatility that allows exploring surface properties at the atomic and molecular levels. Usually, SPM systems deliver information to the user with images that represent the surface properties. Here we implemented a real-time data sonification system that enables visually impaired people to perform SPM experiments and provides other information that is not nicely captured by the human eye. Based on a Raspberry Pi 3B + board and Python algorithms, our system generates parameters based on an SPM scan for sonification that is tested here using the MIDI (Musical Instrument Digital Interface).**

***Index Terms*—microscopy, sonification, data sonification, scanning probe microscopy, auditory feedback.**

I. Introduction

Scanning Probe Microscopy (SPM) is a nanoscience tool that allows investigating the morphology and other local surface properties of samples with spatial resolution better then the atomic level [1]. The SPM techniques consist of raster scanning a sample with a probe, and the data obtained during the probe-sample interaction are converted into images of the analyzed surface [2]. What is proposed in this work is the development of instrumentation and algorithms for the sonification of the data obtained during the real-time scanning in an SPM system.

The sonification provides information using audio so that the system user obtains a new understanding of the data or processes under investigation via sound [3] [4]. In addition to the importance of allowing the visually impaired to perform SPM experiments, data sonification has the potential to provide researchers with a new perspective on the characteristics of the material under analysis [5] because the human ear is able to detect sound characteristics, different from those detected by the human eyes.

The visual and the auditory systems have complementary points in the perception of data. While visual displays can provide representations of selected locations in data sets, auditory scanning may be better suited for detecting subtle or transient data, since hearing can detect characteristics of signals with very short time duration more intuitively [6]. Some experiments already performed have shown an improvement in the performance of the data exploration using visualization combined with sound [5] [7] [8]. These experiments provide a basis for the concept that sonification can be used as a complement to the visual display of data. This promotes an increase in the amount of information conveyed to the user, while reducing the amount of information that the user will need to visually distinguish.

For the specific case of SPM, Martini et al. [5] presented an interactive audio-haptic interface for the control of an atomic force microscope (AFM), addressing different levels of sonification, including raw data and its conversion into sound signal, and a techinique Model Base Sonification (MBS), as proposed in ref. [4]. MBS consists in the use of virtual variables for the interpretation of the force difference applied to a sensor element (commonly known as *cantilever*). However, Polotti [9] questions that there is no real evaluation of the proposed interactive sonification method, since it uses virtual objects in the interaction and a sound model parameterized as auditory display, which does not characterize a sonification/direct interaction of the acquired data. Here we report the implementation of a system for real-time AFM data sonification, which enables the development of new evaluation methodologies, as well as real-time information allowing the user to act in the calibration and adjustment of SPM systems while performing an experiment.

II. Metodology

Among the existing SPM techniques, AFM, which stands out for the versatility and simplicity of application in several types of materials, such as conductors, insulators, biological

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materials, among others [10], was chosen for the development of this work.

The scanning process of an AFM consists of scanning a sample with a probe and, from the probe-sample interaction, generating a hight profile of the probe along the Z axis as it scans the surface in the XY plane (Fig. 1).

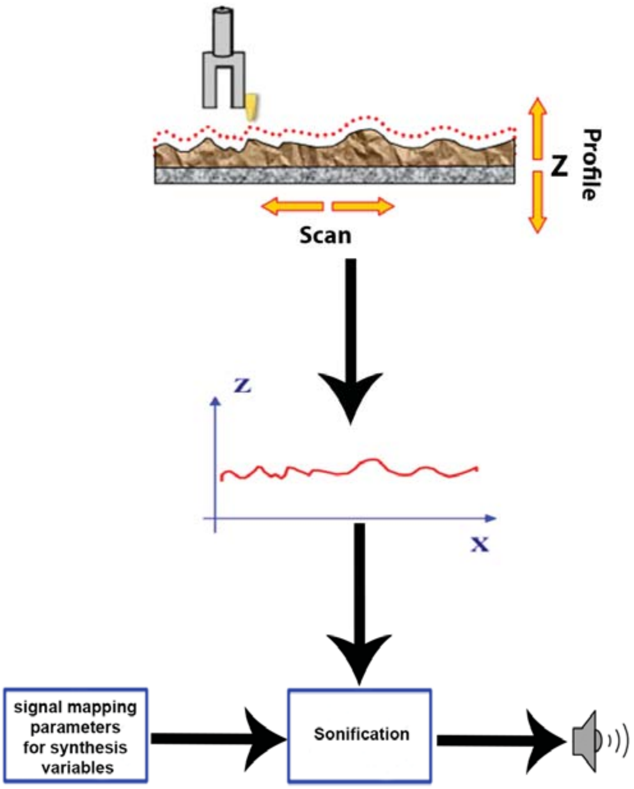

Fig. 1. Schematic representation of the AFM scanning and the sonification processes.

Throughout the scan, an electrical voltage signal proportional to the position of the probe in the Z axis, representing the topographic profile of the sample, is collected. This analog signal is then rescaled to a suitable range and then converted into digital format by an Analog-to-Digital Converter (ADC). The digital signal representing the topography is the input to the sonification algorithm, as shown in Fig. 1. This setup enables the real-time sonification of the topography information.

During the sonification process, the data has to be converted into audible frequencies, usually between $20Hz$ and $20kHz$ [4], in order to be perceived by the human ear. In this work, lower frequency sounds represent the position of the Z-probe at the lower points on the topographic profile. Higher frequency sounds represent the position of the Z-probe at the higher points on the topographic profile.

A. AFM Experimental Setup

An AFM system with PLL (Phase Locked Loop) was used to enable shear-force feedback [11] [12] for a scanning probe attached to a tunning fork (TF). This method is known as TF-AFM [11] and it is performed in a non-contact mode [1]. At the edge of the tuning fork a sharp tip (probe) is attached, and mechanically excited at the tunning fork resonance frequency by a piezoelectric element, called *dither*. When the TF oscillates, the piezoelectric effect of the quartz crystal generates an electric potential between the electrodes that is proportional to the deformation amplitude of the tuning forks [11]. Fig. 2 shows the basic schematics of the described AFM system.

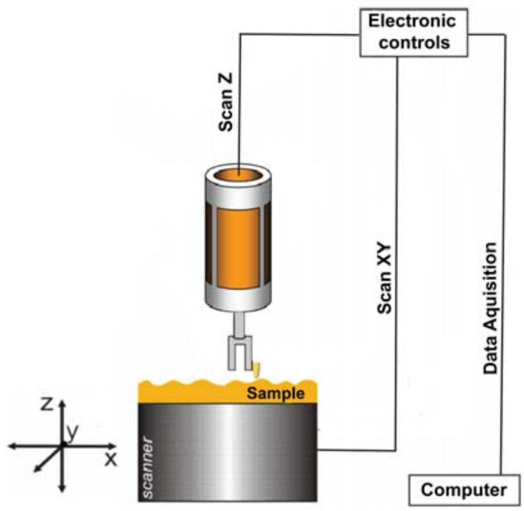

Fig. 2. Schematics of an AFM system based on a tuning fork.

When the probe interacts with the surface, there is a change in tuning fork resonance frequency. The frequency variation (Δf) is related to the probe-sample distance. Δf is then used as a position sensor for a control loop that maintains a constant distance between the probe and the sample surface, by applying a voltage to a piezoelectric tube that changes the probe position along the vertical Z axis.

Based on the system described above, the sonification process will consist of reading the voltage signal applied to the piezo electric tube and converting it into an acoustic signal. The steps of sonification of the generated signal are described in Fig. 3.

B. Signal Acquisition Details

For the AFM control, a developed system based on the R9 controller, manufactured by RHK Technology [13] was used. This system provides a low voltage output, proportional to the position of the probe along the Z axis, whose range varies between $-2.5V$ and $+2.5V$. The $+2.5V$ value represents the upper limit for topography and the $-2.5V$ represents the lower limit.

The signal is then converted into the range of $0V$ to $3.3V$ for compatibility with a Raspberry Pi 3B+ board [14] used for

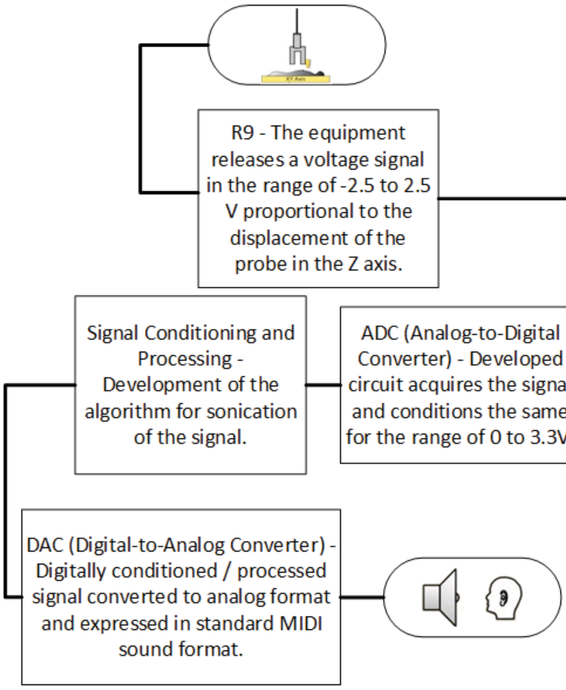

Fig. 3. Flowchart of the sonification process stages for the signal generated by a tunning fork based AFM system.

digital conversion. For circuit implementation, we chose to use the circuit known as zero span [15], [16], wich is often used in instrumentation and measurement processes. This circuit adjusts the signal's slope and offset. The implemented circuit is shown in Fig. 4. Eq. 1 represents the mathematical model that describes this circuit.

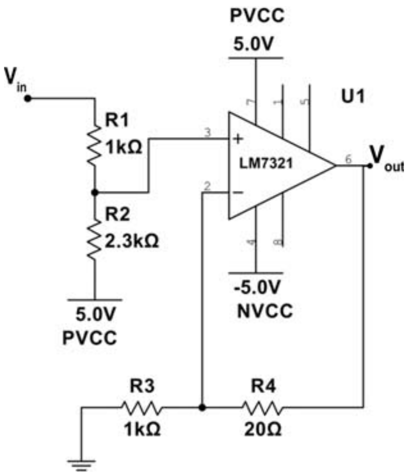

Fig. 4. Proposed circuit for conditioning the signal acquired from the R9 controler.

$$V_{out} = 1.02 * \left(\frac{2.3V_{in} + 5}{3.3}\right) \tag{1}$$

The circuit output was connected to an ADC for conversion of the read signal. The ADS1115 [17] was used for signal conversion. Communication with the Raspberry Pi was via I2C protocol [18].

C. Implementation of the data sonification system

The sonification process consists of reading the voltage signal applied to the piezoelectric tube, which corresponds to the position of the probe relative to the Z axis, and converts it into an acoustic signal. Fig. 5 describes the steps of sonification of the signal acquired from the AFM system.

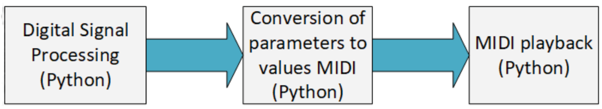

Fig. 5. Flow chart of the sonification process of the signal generated by an AFM system based on a tuning fork.

In order to implement the sonification procedure, it is necessary to reduce the number of samples to the minimum possible, considering the acquisition rate of $860 samples/s$, acquisition rate configured in ADS 1115 according to manual, keeping fidelity to the topographic profile. With this porpuse, the signal was decimated. In decimation, the sampling rate is reduced from F_s(sampling frequency) to F_s/M by discarding $(M - 1)$ samples for all sets of M samples following the acquired signal. The formal definition of decimation is defined by

$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[nM - k]] \tag{2}$$

where h[k] represents the *anti-aliasing* filter, usually a lowpass Chebyshev FIR filter, applied to avoid the distortion effect, due to the reduction of the sampling rate.

If the sampling rate was simply reduced by selecting a single sample for each M samples in $x[n]$, the resulting signal would be an aliased version of $x[n]$. To avoid aliasing, we must first reduce the bandwidth from $x[n]$ to $F_{max} = Fx/2M$, where F_{max} is the maximum frequency of the acquired signal [19]. Thus, for the sampled scanning signal, the frequency obtained through the Matlab Signal Analyzer was $36Hz$, with the value of M equals 12 found to perform decimation of the acquired signal.

The choice to adjust the sampling rate after the acquisition was done in order to increase the systems flexibility. This allows the user to finely tune the signals sampling to best match the frequency components for a given sample.

After decimaton, the digital signal representing topography is supplied to the sonification algorithm. Is this step, each topography datapoint is converted to a sound signal that is played for a fixed period of time.

For the sonification program the Python programming language was used in combination with Pygame library for sound reproduction and Numpy, the fundamental package for scientific computing with Python. Among the many features offered by this library, a MIDI (Musical Instrument Digital Interface) module for interactions with MIDI inputs and outputs is available. A MIDI signal is an Integrated Digital Musical Interface signal that has key parameters of pitch velocity (volume), tone, and note length. Each of these parameters can be assigned values ranging from 0 to 127 [20].

The velocity values in MIDI correspond to how strong a virtual note is played, with 0 being weaker, which in terms of volume the note would be inaudible and 127 being the strongest. The pitch values correspond to the range of musical notes that can be related to a MIDI note, with 0 being $C0$ and 127 being $G10$. The duration of each note is not changed at run time to make the sound pattern more consistent when playing the topographic data. A feature of interest offered by this library is the possibility of using different musical instruments. With this option it is possible to obtain different sound feedbacks that can be adjusted in order to obtain a better sound quality [20].

Within this context, an algorithm was developed to convert the voltage signal corresponding to the position of the probe on the Z-axis into a MIDI musical note. The basic structure of the algorithm consists in converting the value of the scan into a note and then reproducing it with an audio output device, according to Algorithm 1.

Algorithm 1: read_scan

Data: Voltage signal corresponding to the position of the probe on the Z axis
Result: Play song in function position of the probe on the Z axis
Input: votageval
while $true$ **do**
  $cont$ ←cont+1
  if $cont = 12$ **then**
    $note \leftarrow get\_note(voltageval)$
    $play\_midi(note, prevnote, volume)$
    $cont = 0$

This conversion process was performed using proportions. When voltage = minvolt, the resulting note will be the lowest note (minNote). It is similarly done at the other end of the scale. This allows the algorithm to define the relationship between the probe distance and the steps of each note in a function form. This function is evaluated every time a voltage value (volt) is measured, according to the Algorithm 2. In relation to the lowest note (minNote) and highest note (maxNote), the minNote is a fixed value defined within the scale of 0 to 127, the value of maxNote is calculated as a function of the number of octaves to be added to the value of the minimum note. The number of octaves can be changed as required.

Once the musical notes are set according to the scan value, the note is then played to the user through the $play\_midi$ function, Algorithm 3. This function holds a sound output and changes it based on each topographic datapoint supplied by the decimation algorithm, thus generating a new sound pattern to

Algorithm 2: get_note

Data: Voltage to conversion
Input: voltageval,minNote,minVolt,maxVolt
Result: Get note in function of voltage value
$note = minNote + ((voltageval - minVolt) * (maxNote - minNote))/maxVolt - minVolt$
return *note*

be played, thereby representing the topographic variations with a variation of sound signal throughout the scan.

Algorithm 3: play_midi

Data: MIDI note generated by the get_note function
Input: note,b4note,volume
Result: Play MIDI sound
if *note != b4note* **then**
  $play.note\_off(b4note, volume)$
  $play.note\_on(note, volume)$

III. Results

To test the algorithm developed based on conversion to MIDI notes, it was implemented on the Raspberry board, which received the scan data through the developed circuit that was connected to the low voltage output of R9, so that the scan data was processed simultaneously. An AFM pattern calibration standard was used, model TGZ02, manufactured by MicroMasch, according to Fig. 6.

The silicon calibration grid of the model used comprises a matrix of rectangular steps with a height value characterized for the calibration of the Z axis of SPM equipment. The pattern has the characteristics described in Fig. 6 and Table I.

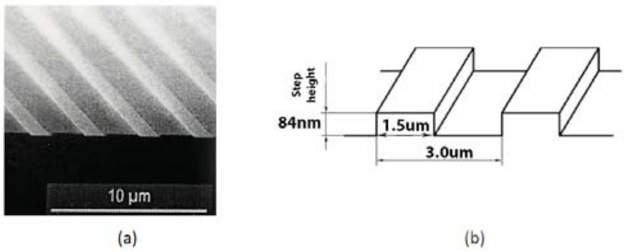

Fig. 6. In (a) an image of the AFM calibration standard generated by scanning electron microscopy. In (b) the dimensions of the grids in the model. (Adapted from MicroMasch model TGZ02 model manual.)

TABLE I
CHARACTERISTICS OF THE STANDARD SAMPLE SHOWN IN FIG. 6

Feature	Dimension
Area	$3 \times 3\ mm^2$
Step height	$84\ nm$
Step Width	$1.5\ \mu m$
Precision	$1.5\ nm$
Period	$3.0\ \mu m$

The scanning process is shown in Fig. 7. The start and end limits of the line correspond to the scanning area defined in the SPM system, the final scan image being composed of the information collected in both directions of scanning, Forward and Reverse.

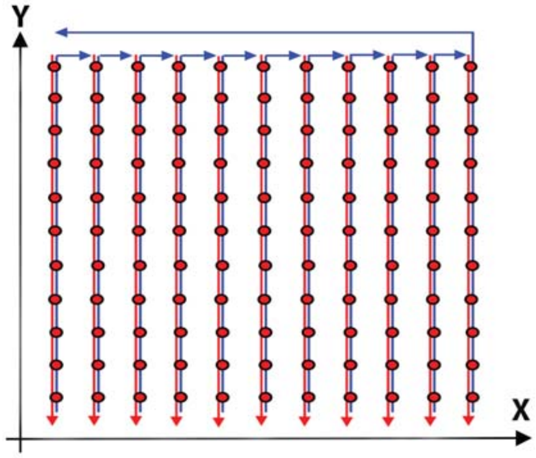

Fig. 7. Schematic illustration of the scanning process. The direction of forward movement is indicated by red arrows. The reverse movement is indicated by blue arrows. Points represent information collection locations.

Once the AFM scanning system was set up, an area of $6 \times 6 \mu m^2$ of the total AFM scan area was selected. The result obtained with the scan performed can be seen in Fig. 8 (a). In ideal conditions the surface of the pattern is completely flat, so the profile should be linear in each level. Due to dirt particles as well as small deformations in the part of the probe that interacts with the surface of the pattern, the topographic profile presents some defects, as can be seen in Fig. 8 (b). A scan line, marked by the black line in Fig. 8 (a), was selected to highlight the failures reported above. The topographic profile of the line can be seen in Fig. 8 (c), which consists of the data acquired in the forward scanning direction.

Notice the detail levels of the sample surface. When the data is analyzed via software, with visual feedback to the user, subtle details of the surface are often overlapped or unified by the data processing system for conversion into image. Fig. 9 represents the section marked in Fig. 8, validating that the system acquires scan data compatible with the topographic variations of the sample.

Connecting the sonification system developed to the SPM R9 control system for real-time reading of the scanning data, it was possible to perceive sound variations corresponding to the variations of the topographic profile of the sample. After performing the voltage conversion process for the MIDI musical note, and its sound reproduction, a graph was generated with the note values obtained to validate if the conversion was compatible with the topographic profile generated by the visual feedback system used by the SPM system, as shown in Fig. 10.

After performing the voltage conversion process for the MIDI musical note, and its sound reproduction, a graph was

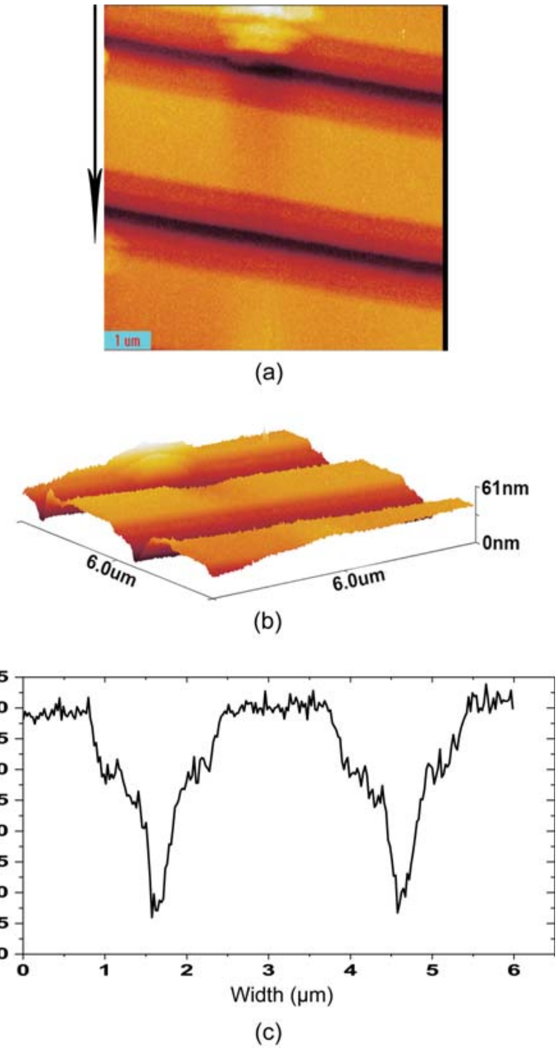

Fig. 8. Signal acquired while scanning the standard. In (a) the scanning signal is show as 2D image post-processed; In (b), 3D image of the standard scan, with surface details; and In (c) signal corresponding to the black section marked in Fig. 8 (a)

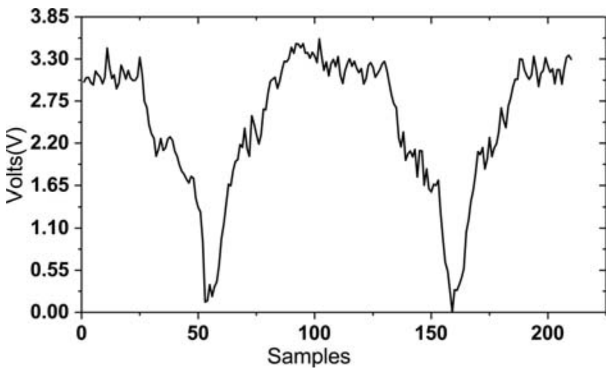

Fig. 9. Topographic scanning signal of the AFM calibration standard obtained with the AFM scan, marked in Fig. 8 (a) by the black line.

generated with the note values obtained, to validate that the conversion was compatible with the topographic profile generated by the visual feedback system used by the SPM system, as shown in Fig. 10.

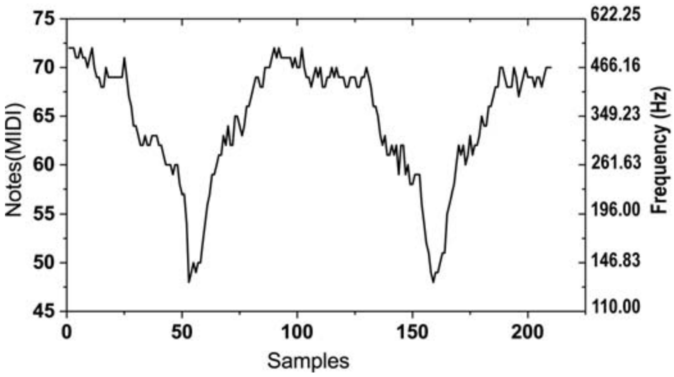

Fig. 10. Graphic of the musical notes generated from the data acquired in the scanning process.

IV. Conclusion

In this article, a system for generating the sonification parameters for the scanning signal of an AFM system was implemented. A sound feedback compatible with the topographic variations that occur during the AFM scanning process was obtained, validating the complementarity between the two modes, also confirming the viability of the visually impaired to perform SPM experiments.

When accomplished the sonification of the data, it was possible to perceive that the sound variations corresponded to the variations of the topographic profile of the sample, thus confirming that the feedback sound of AFM scan in time of aquisition is viable. The direct acquisition opened the possibility of a greater detailing of the sample surface, as well as a better understanding of the process. We tested our system using MIDI, but the system output can reach a sampling up to 2 MS/s, opening the possibility for new studies on more sophisticated sonification processes.

Acknowledgment

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