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Design and control of multi-actuated atomic force microscope for large-range and high-speed imaging ☆

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ABSTRACT

This paper presents the design and control of a high-speed and large-range atomic force microscopy (AFM). A multi-actuation scheme is proposed where several nano-positioners cooperate to achieve the range and speed requirements. A simple data-based control design methodology is presented to effectively operate the AFM scanner components. The proposed controllers compensate for the coupled dynamics and divide the positioning responsibilities between the scanner components. As a result, the multi-actuated scanner behavior is equivalent to that of a single *X–Y–Z* positioner with large range and high speed. The scanner of the designed AFM is composed of five nano-positioners, features 6 μm out-of-plane and 120 μm lateral ranges and is capable of high-speed operation. The presented AFM has a modular design with laser spot size of 3.5 μm suitable for small cantilever, an optical view of the sample and probe, a conveniently large waterproof sample stage and a 20 MHz data throughput for high resolution image acquisition at high imaging speeds. This AFM is used to visualize etching of calcite in a solution of sulfuric acid. Layer-by-layer dissolution and pit formation along the crystalline lines in a low pH environment is observed in real time.

1. Introduction

High speed imaging capability extends the applications of atomic force microscopy (AFM) to the study of dynamic nano-scale processes [1]. The potential advantages of high-speed AFM in enabling novel scientific observations [2] have been the main motivation behind a considerable amount of research efforts to unlock this capability [3–6]. These efforts have resulted in significant improvements in the state of the art and have led to new contributions [7].

To enable high-speed AFM imaging, electrical [8], optical [9], mechanical [10,11] and control [12–15] components of the AFM have been improved. Research on the design of AFM scanners [11,4] has led to rigid designs capable of high scan speeds. Optimal feedforward and feedback control techniques are used to reduce the tip–sample interaction forces at high speeds [14,16]. Active vibration suppression techniques have been applied to tackle the out-of-plane scanner dynamics and extend the closed loop bandwidth of the AFM [12]. The size of AFM micro-cantilevers has been reduced significantly, increasing the probe resonance frequency to a few megahertz while maintaining small spring constant [17]. Furthermore, to enable application of these small probes, the optical beam deflection setup has been modified [9,18].

Increasing the bandwidth performance of the AFM scanner while maintaining a reasonable scan range is currently one of the most challenging aspects of high-speed atomic force microscopy research. This limitation is rather fundamental. Wider mechanical bandwidth requires increased rigidity and reduced translated mass, which naturally leads to decreased lateral and out-of-plane scan ranges [11,17]. Small out-of-plane range limits the application of AFM as the topography height variations due to sample tilt [13] or thickness, e.g. cells [19] may necessitate several microns of travel. Limited lateral range is likewise problematic as sample features of interest can span a large area in many imaging applications or site of interest can be situated away from the active scan region. To simultaneously achieve the range and speed requirements of the out-of-plane AFM actuator, researchers have applied dual actuation methodologies [13,20–29]. In this approach, emanating from hard disk drive (HDD) research [30], two out-of-plane nano-positioners are combined where one is fast and short-range and the other slow and large-range. These earlier works on multi-actuation, which are all limited to out-of-plane motion of the scanner, can be divided into two main categories. In one, self-actuated AFM probes are used in combination with external piezos [23,24]. This approach suffers from either the bandwidth or range limitations of bimorph actuators [23] or the complexity of

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attachment and actuation of magnetic particles [24]. In the second category [20–22,25], two external piezo actuators are used on independent substrates where one moves the sample and the other moves the probe. This arrangement avoids dynamic coupling, but limits the technique to only two actuators and requires modifications in the optical path of sample-scan AFMs. In this work we present a new multi-actuated atomic force microscope which features a number of practical advantages. We extend the concept of multi-actuation to all scan directions, enabling large-range and high-speed performance for both lateral and out-of-plane motion. The proposed methodology is presented in a generalized form applicable to any number of actuators. All the actuators are cascaded in series and unified into a single package, making it applicable in any AFM setup (sample-scan or probe-scan) without a need for modifying the optics. The control of the multi-actuated AFM is kept resilient to variations natural to atomic force microscopes (e.g. changes in sample stage, imaging mode, imaging environment, etc.). A multi-actuated scanner is designed based on the proposed method. The designed scanner has 120 µm lateral and 6 µm out-of-plane range and is capable of high-speed imaging, featuring a combination of functionalities reported here for the first time. Furthermore, the scanner design ensures that the scan axes are kinematically decoupled. The designed AFM features a large (15 mm diameter) waterproof sample stage with fully vertical approach mechanism, an optical head with 3.5 µm laser spot size and an image acquisition platform with 20 MHz data throughput capable of capturing high resolution images at video rate.

2. Multi-actuated atomic force microscopy

2.1. The notion of multi-actuation

The advantage of utilizing multiple actuators in atomic force microscopy is rooted in the fact that for both lateral and out-of-plane motion of the scanner, the travel range requirements are less stringent at higher frequencies. The out-of-plane motion is dictated by the spatial frequency content of the sample surface topography which commonly contains low amplitude/high spatial frequency and large amplitude/low spatial frequency features. Similarly, the high frequency components of the raster command input to the lateral scan actuators are localized near the turnaround points which constitute a small portion of the scanning range. Decomposing a triangular raster scan command signal to its Fourier components shows that 81 percent of the scan range is accommodated by the first harmonic of the series, with all higher harmonics forming the remaining 19 percent. These observations imply that high-speed and large-range nano-positioning is possible if one combines slow and large-range actuators with those of wider mechanical bandwidth and shorter range.

2.2. Cascaded series of multiple actuators

In the simplest form of multi-actuation, several actuators are cascaded in series, sorted from the largest (slowest) to smallest (fastest). Fig. 1a schematically demonstrates this arrangement where each actuator is represented as a 2nd order system with an incorporated actuation force. Although this arrangement of multiple actuators is practically appealing, it leads to dynamic coupling and thus necessitates dynamics compensation. The compensation can be done through a series of independent controllers. The control arrangement of Fig. 1b is proposed for multi-actuated out-of-plane topography tracking. In this form the system is robust to variations natural to AFMs. This is because the multi-actuation control for out-of-plane motion is designed auxiliary to a common PID unit. The design of auxiliary control units, G_n^{v}, are discussed in Section 2.4. The auxiliary control ensures that the multi-actuated scanner behaves similarly to a single high-speed and large-range actuator while the PID unit can be adapted to experiment specific needs. The control arrangement of Fig. 1c is proposed for multi-actuated lateral raster scan. In the open loop form, a Fourier decomposition unit (denoted by FD) distributes various frequency components of the command signal to each actuator. The hysteresis behavior of a multi-actuated system is influenced by that of the individual components. It is very important to note that the combined hysteresis effect of multiple piezo actuators cannot be represented by a single hysteresis model. The hysteresis nonlinearity of each scanner actuator should be modeled and treated independently. For the proposed feedforward control of the multi-actuated lateral positioner, the hysteresis compensation [15], denoted by H^{-1}, can be implemented in line with the dynamics compensation stage (Fig. 1c).

Each of the lateral (superscript l) or out-of-plane (superscript v)

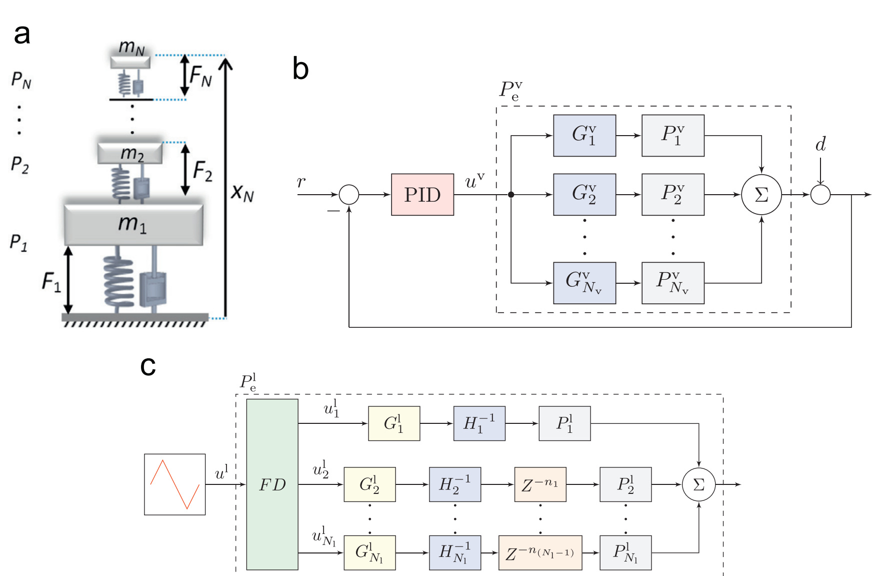

Fig. 1. (a) Cascaded arrangement of multiple actuators, modeled as a serial connection of several 2nd order systems; proposed schemes for the control of (b) multiple out-of-plane actuators and (c) multiple lateral actuators.