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Development of nanomanipulator using a high-speed atomic force microscope coupled with a haptic device

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ABSTRACT

The atomic force microscope (AFM) has been widely used for surface fabrication and manipulation. However, nanomanipulation using a conventional AFM is inefficient because of the sequential nature of the scan-manipulation scan cycle, which makes it difficult for the operator to observe the region of interest and perform the manipulation simultaneously. In this paper, a nanomanipulation technique using a high-speed atomic force microscope (HS-AFM) is described. During manipulation using the AFM probe, the operation is periodically interrupted for a fraction of a second for high-speed imaging that allows the topographical image of the manipulated surface to be periodically updated. With the use of high-speed imaging, the interrupting time for imaging can be greatly reduced, and as a result, the operator almost does not notice the blink time of the interruption for imaging during the manipulation. This creates a more intuitive interface with greater feedback and finesse to the operator. Nanofabrication under real-time monitoring was performed to demonstrate the utility of this arrangement for real-time nanomanipulation of sample surfaces under ambient conditions. Furthermore, the HS-AFM is coupled with a haptic device for the human interface, enabling the operator to move the HS-AFM probe to any position on the surface while feeling the response from the surface during the manipulation.
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0. Introduction

The atomic force microscope (AFM) has been widely used as a surface imaging tool with nanometer-scale resolution. The AFM uses a probe to scan the sample surface to obtain the surface topography. The AFM has also been used as a local surface fabrication tool. By using the probe, an operator can fabricate nanometer-scale objects or move them under a variety of conditions (i.e, vacuum, air or liquid), and thus manipulators using AFMs are expected to become powerful tools in various fields. Several studies concerning such manipulations using an AFM have been performed [1–9]. Recently, to improve the operationality of AFM manipulation, haptic technologies have been introduced in nanometer-scale manipulations of various materials such as carbon nanotubes [10–14], fibrin fibers [15,16], nano particles [17] and DNA [18]. The haptic technology supplies an interface between the operator and the apparatus for applying forces to the objects via the operator's sense of touch. These studies showed that using a haptic devices an operator can directly move an AFM probe on the sample surface and feel the response from its surface during AFM manipulation. Thus, the haptic technique is very useful for nanometer-scale manipulation and fabrication not only for material sciences but also for biological fields. However, one drawback of such nanometer-scale manipulation using a conventional AFM is that the manipulation scenes cannot be monitored during the operation. Because of the lack of real-time visual feedback, the operator has to move the probe blindly, which often causes damage to the sample or probe during the operation. After each manipulation operation, a new image must be obtained to verify the manipulated surface, and then the next operation can be started. This "scan-manipulation-scan" cycle is very time-consuming, because the conventional AFM has the major disadvantage of a low imaging rate, requiring typically a minute or more to acquire an image. Therefore, real-time monitoring systems have been desired during manipulation. To improve the imaging speed, several research groups have recently developed high-speed AFMs (HS-AFMs) [19–26]. The HS-AFMs allow direct visualization of dynamic processes of structural changes at high spatiotemporal resolution, which might be effective for nanometer-scale manipulation.

In this research, we developed an interactive nanomanipulator by coupling a haptic manipulation system with a HS-AFM. Using this system, it is possible for the operator to move the AFM probe to any

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position on the surface while feeling the response from the surface during manipulation. The AFM image of the manipulated surface is periodically updated during the manipulation operation, and thus the operator can manipulate the surface while confirming the manipulation scene with real-time observations. In this study we investigated the feasibility of the manipulation system HS-AFM. To demonstrate the system, we performed nanometer-scale manipulation of polycarbonate and collagen fibrils under ambient conditions.

1. Experimental details

1.1. High-speed AFM coupled with a haptic device

The system developed here is based on a HS-AFM. With respect to HS-AFM techniques, several methods were reported previously, as described above. Here we employed a high-speed imaging method detected from cantilever deflection in contact mode [24]. Fig. 1(a) shows a schematic diagram of the assembled scanner for high-speed imaging. The HS-AFM was constructed within a homemade AFM. A tiny shear piezo stack was employed as a fast scanner (Fuji Ceramics Corporation, Japan). The scanner is 3 mm-wide, 3 mm-deep and 4 mm-high, with a bandwidth of 10 kHz. The sample was glued directly onto the shear piezo scanner, which was in turn mounted on the top of a conventional XYZ piezotube scanner. The sample was scanned in the *x*,*y* plane beneath the tip of the cantilever using the high-speed scanner in order to generate the fast scan axis and using the conventional piezotube scanner to generate the orthogonal slow scan *y*-axis and average feedback of vertical *z*-axis.

In a conventional AFM, an electronic feedback loop is used to maintain a constant deflection of the cantilever to follow the topography of the sample by adjusting the position of the sample relative to the tip. In the HS-AFM, high-speed imaging is carried out from deflection of the cantilever under the passive mechanical feedback system [24], which produces highly repeatable and accurate data at scan speed of up to 5 mm/s [27] with low noise imaging [28].

Fig. 1(b) shows a schematic diagram of the HS-imaging and manipulation system. For HS-imaging, the deflection signal is directly acquired with an analog-to-digital (A/D) converter of the personal computer. For manipulation operation, we used a haptic device that has a pen-like handle with a serial link mechanism (PHANTOM Omni; SensAble Technologies) to be coupled with the homemade AFM [29]. With respect to lateral movements in the *x* and *y* directions, a signal from the haptic device is sent to the personal computer, and then the signal is sent to the piezo drive circuit passing through a digital-to-analog (D/A) converter. The topographical signal detected in the AFM controller is fed to the personal computer where it is converted to the displacement in the *z*-direction of the pen handle of the haptic device. Via this process, the nanometer-scale topography on the surface can be felt in the operator's fingers holding the pen handle. By this sequential process, the operator can manipulate the surface by feeling the response from the surface via the haptic device.

1.2. Sequence for real-time manipulation

In general, the standard manipulation process using a conventional AFM is as follows. First, the surface topography is ascertained just before the manipulation by the AFM, and then the topographical image is displayed on a PC screen. Starting up the process takes several minutes at least. After obtaining the image on the screen, the operator moves the AFM probe using a mouse to perform

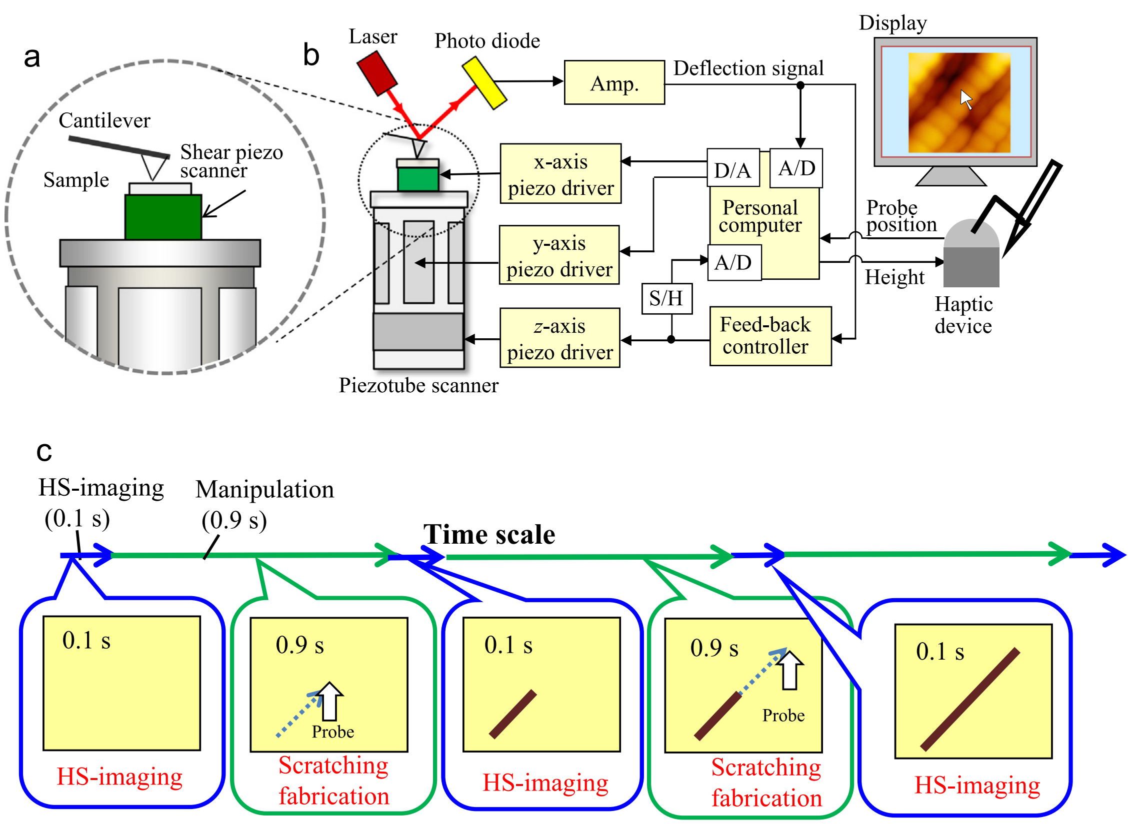

Fig. 1. A schematic diagram of the experimental setup of an AFM manipulator. (a) The assembling of the scanner for high-speed imaging. The sample is mounted on a shear piezo actuator that generates the fast scan *x*-axis. (b) The AFM is coupled with a haptic device; thus, the operator feels the response from the sample during manipulation operation. (c) A sequence of the manipulation using the system. In the manipulation program, a one-cycle period consists of manipulation phase plus imaging phase, which is sequentially continued repeatedly using the same AFM probe via time sharing.

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