# Slip-stick step-scanner for scanning probe microscopy

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A slip-stick positioning system is shown to work as a step-by-step scanning device. Scanning confocal optical images with sizes up to 100 $\mu$m by 100 $\mu$m were taken in reflectivity using a 635 nm wavelength laser and an objective of numerical aperture=0.8. The images were taken under ambient and cryogenic conditions on samples with periodic patterns as well as with nanomechanical systems. They show exceptional low distortion and high linearity. The use of the slip-stick step motion for image scanning simplifies the scanning confocal microscope since the long-range positioning unit and the scanning unit merge into only one unit that can do both.
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## I. INTRODUCTION

Compact and stiff translation stages based on the principle of inertial slip-stick step motion are commonly used in order to position the sample in a scanning probe microscope. These slip-stick translation stages provide a fine positioning of the sample in the nanometer range, but until now have not been used to generate the scanning motion for imaging. This is because the step sizes not only vary by a few percent from step to step, but also differ substantially in forward and backward directions. These systematic cumulative step size errors would result in highly distorted images. We have discovered an operation mode in which the slip-stick translation stages self-correct the systematic step size errors. As a result, we succeeded in obtaining undistorted images with a confocal microscope by slip-stick step-scanning the sample through the focused light spot. The images of well characterized nanostructures taken over an area of up to 100 $\mu$m $\times$100 $\mu$m with a diffraction-limited resolution of 0.6 $\mu$m are typically composed of some 10 000 pixels and show that the cumulated step size errors were a few pixels only. This finding makes the use of inertial translation stages an attractive alternative to delicate and bulky linearized scanning stages.

Scanning probe microscopes usually contain a piezoelectric stage that allows a controlled displacement of the probe in relation to the sample. An image is formed by the sequential acquisition of pixels during the scanning motion of the stage. Scanners using a lead zirconate titanate (PZT) piezoelectric ceramics are often limited in scanning range and this especially at cryogenic temperatures. They also produce an undesirable nonlinearity and a hysteresis in the images. Many scanning probe microscope designs additionally include a compact and stiff translation stage actuated by inertial slip-stick motion to position the sample over millimeters with step sizes in the nanometer range. One could in principle use this nanometer-fine step-by-step motion to generate the scanning sequence for imaging. This is generally not done because it is thought that step sizes are prone to systematic errors. Unexpectedly, however, our results prove this common wisdom wrong. In this article, we show that a two-dimensional slip-stick piezoelectric stepper can be used as a scanning imaging device that scans step by step. We show how to "train" the translation stage to produce images exceptionally free of distortions. This mode of imaging does not require feedback or software correction. Instead, a self-correction mechanism was found that is very likely to originate from the nature of the friction involved. The underlying physics is not yet understood, but studying the slip-stick device could teach us how to exploit tribology in order to do metrology.

## II. SLIP-STICK INERTIAL TRANSLATION STAGES

We used a slip-stick inertial translation stage as a step-scanner in a confocal optical microscope and took images with each pixel corresponding to a step. In this step-scanning mode we obtained confocal optical images that are exceptionally reproducible and linear. The physics behind this effect is presently not understood. The samples we imaged are nanoelectromechanical devices that we produced out of silicon-on-insulator wafers. The smallest of these structures are freestanding nanocantilevers of 10 $\mu$m$\times$200 nm $\times$120 nm. The images taken over an area exceeding 100 $\mu$m$\times$100 $\mu$m were directly compared to scanning electron images of the same samples, confirming that no measurable distortion is introduced through this scanning method.

Translation stages based on slip-stick motion have been used in a variety of applications[1–5] ever since their invention by Pohl in 1987.[6] The basic principle of translation stages based on slip-stick inertial motion is the controllable use of the inertia of a sliding block. In our slip-stick inertial translation stages,[7] the sliding block slips along a guiding rod to which it is otherwise clamped (sticking) in frictional engagement. To obtain a net step, the guiding rod is first accelerated very rapidly over a short period of time (typically microseconds) so that the inertia of the sliding block overcomes the

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static friction. This way, the sliding block disengages from the accelerated rod and remains nearly nondisplaced. Subsequently the guiding rod moves back to its initial position slowly enough so that the sliding block this time around sticks to it and thus makes a net step. Periodic repetition of this sequence leads to a step-by-step motion of the sliding block in one direction. A piezoelectric ceramics pushes or pulls the guiding rod and the exact sequence in the slip and stick motion is controlled by an appropriate voltage signal. The main challenge of using slip-stick translation stages for imaging is to obtain a reliable and controllable motion of the sliding block over millimeter ranges and with small and reproducible enough steps. The main technical challenge is to control the frictional engagement. The design of our rod and sliding block is such that all surfaces in frictional contact are planar, producing this way a homogeneous and constant frictional force engagement. In this work, we obtained images over a large scanning range and this without using any active servo or software correction, such as is implemented to linearize piezoelectric actuators. A major benefit of this result for confocal microscopy is that large scanning ranges can be obtained even at cryogenic temperatures, where PZT piezo ceramics are limited to scanning ranges of only a few microns.

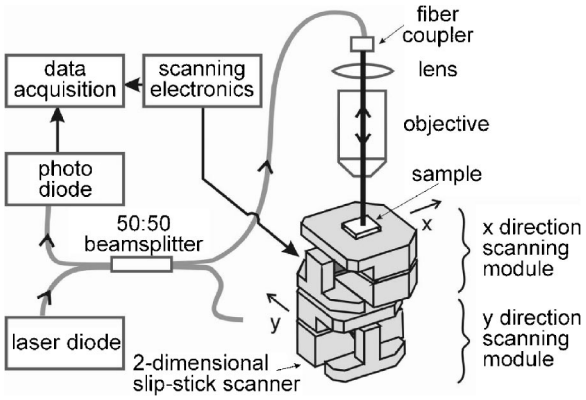


FIG. 1. Confocal slip-stick step-scanning optical microscope. The light of a laser diode (wavelength 635 nm) is launched into a single-mode optical fiber [2 m long and with a numerical aperture (NA) of 0.12]. At the other polished end of the fiber, the light is collected and collimated with a first lens (focal length=15.36 mm, diameter=5 mm, NA=0.15). The collimated beam fills the back aperture of an objective (Olympus, focal length =1.8 mm, NA=0.8, working distance=3.4 mm) placed at a distance of a few centimeters from the first lens. The objective focuses the light to a diffraction-limited probing spot with a full width at half-maximum of about 600 nm. The backscattered light retraces its path through the objective and through the collimating lens to be collected in the single-mode fiber. A 2 $\times$2 fiber beam splitter directs half of the backscattered light toward a conventional Si photodiode with a current-to-voltage converter and amplifier (Thorlabs PDA 55). Pixel-by-pixel scanning of the positioner (atto**cube** systems ANPx100) and recording of the signal results in an image.

## III. SETUP FOR SCANNING AND IMAGING

The optical setup consists of a confocal optical microscope arrangement as shown in Fig. 1 operating at 635 nm wavelength with diffraction-limited resolution.[8] To take an image, we used two slip-stick inertial translation stages[7] mounted on top of each other to provide motion along the scanning plane (*xy*-plane), as shown schematically in Fig. 1. To position the sample along the optical axis (*z*-axis) of the confocal microscope, a third slip-stick inertial translation stage was used. In each translation stage, a 13 mm long titanium guiding rod with a square section of 5 mm$\times$5 mm is attached to a PZT ceramics mounted on the frame of the translation stage. The sliding block is made of two titanium parts that are spring loaded to each other as to sandwich the guiding rod between them. A v-groove that matches the square cross-sectional shape of the rod is machined in each of the two sliding block parts in order to provide both frictional holding to the rod and axial guidance of the motion. The translation stages for in-plane displacement have a height of 14.5 mm and a footprint of 24 mm$\times$24 mm. The *z*-translation stage has a height of 25 mm for the same footprint.

A net single-step motion of the sliding block toward the piezoelectric actuator occurs when a voltage pulse with a short rise time of 3 $\mu$s and a much longer decay time of 1 ms is applied to the piezoelectric ceramics. The amplitude of the voltage is set between 5 and 24 V to obtain a step size ranging between about 40 and 400 nm at room temperature. At 4.2 K, step sizes smaller than 5 nm were obtained. An in-

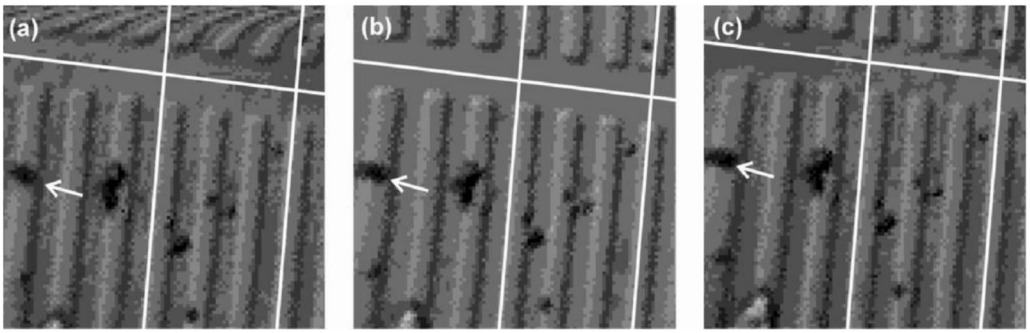


FIG. 2. Slip-stick step-scanned confocal optical micrographs (100$\times$100 pixels) of parallel stripes of silicon dioxide on silicon (period: 4 $\mu$m). We acquired pixels from left to right in a fast scan to make a line at a rate of 1 ms per pixel. With a subsequent shift in the perpendicular direction, lines were then accumulated from top to bottom to make an image. The straight white lines are a guide to the eye to help assess possible distortions in the image. (a) When the scan is run for the first time, the acquired image shows very strong distortion in the first few lines (top of the image). After about 10 to 15 lines, the horizontal translation stage locks into a mode for which forward and backward scanning have identical lengths, and thus the image distortions disappear. The arrow points to an arbitrary feature in the image that will be recognized in the subsequent images. (b) The image taken right after the first one is undistorted from the beginning since the step-scanner now operates in its locked mode. (c) We repeated the scan one more time to show that the image is nearly perfectly reproducible in any subsequent scan.

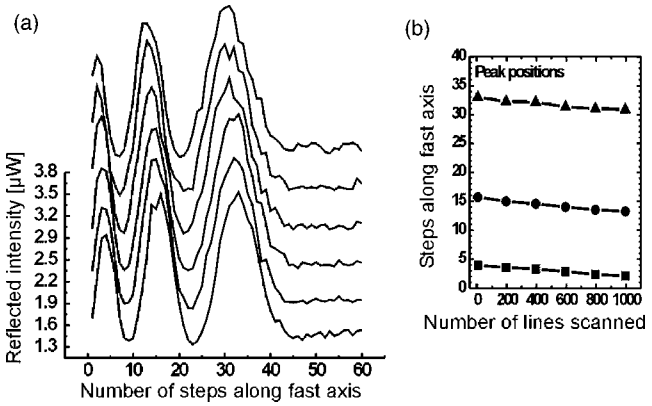


FIG. 3. This figure shows the results of a line repeatedly scanned. A 60 pixel line was scanned 1000 times forwards and backwards with steps of a voltage amplitude of 12 V (corresponding to a step size of about 130 nm). The incident laser power was 150 $\mu$W. (a) The plot shows a line image of the forward scan about every 200 repeats. To reduce random noise, each line shown is an average over ten lines, between every two lines we introduced an offset for clarity. In every scan, three reflectivity peaks appear that always have about the same shape. Their position shifts by only about two pixels from the first to the thousandth line, as can be directly seen from the plot of the peak positions against the lines scanned (b).

crease of the voltage up to 70 V at 4.2 K leads to step sizes as large as 120 nm. Periodic repetition of the voltage sequence can be made as quickly as 1 kHz. To reverse the direction of the single-step motion, the voltage rise is done slowly (at 1 ms) and the subsequent decay is done quickly (3 $\mu$s). Two translation stages mounted perpendicularly on top of each other, as shown in Fig. 1, allow a two-dimensional step-by-step slip-stick scanning. A sequence of pixels is produced by scanning the sample under the imaging spot step by step while recording a signal at each position. The total image acquisition scan time was limited by the time needed for a single step, which was dominated by the slow voltage-decay time of about 1 ms. In our scanning sequence, first, one of the in-plane translation stages (the so-called fast axis) makes $N$ steps forwards in either $x$ or $y$ direction. It then performs $M$ steps backwards along the same axis. Once this is completed, a line in the image is acquired and the second translation stage (the slow axis) makes one single step in the perpendicular direction to allow the acquisition of the next line. At the end of the image acquisition, the slow axis is moved back to its initial starting position.

## IV. MEASUREMENTS AND DISCUSSION

All of the optical slip-stick step-scanned confocal images shown here were generated at room temperature and in air. This being said, we verified that slip-stick step-scanning imaging worked at temperatures as low as 50 mK and under high vacuum ($10^{-9}$ mbar) condition.

When we first started the experiment, we thought that the main difficulty in using this scanning sequence would be that the step sizes in the forward and backward scanning direction are not the same.[9] Thus, even the best possible choice of $N$ and $M$ could not guarantee a perfect match of the forward and backward scanning lengths. Consequently, a resulting systematic mismatch in length would greatly distort the image. We expected that we would not only need to go through a very careful control of the numbers of steps $N$ and $M$, but also would have to control their sizes through the voltage pulse amplitudes. We also worried about a possible drift of these parameters during an image acquisition and thought that slip-stick step-scanning would be prohibitively difficult. Despite our misgivings, none of this was a problem.

### A. Properties of slip-stick step-scanning imaging

We acquired images that were surprisingly undistorted and nearly perfectly reproducible over a very long period of time after the fast axis had already scanned a couple of times back and forth across a scan region we intended to investi-

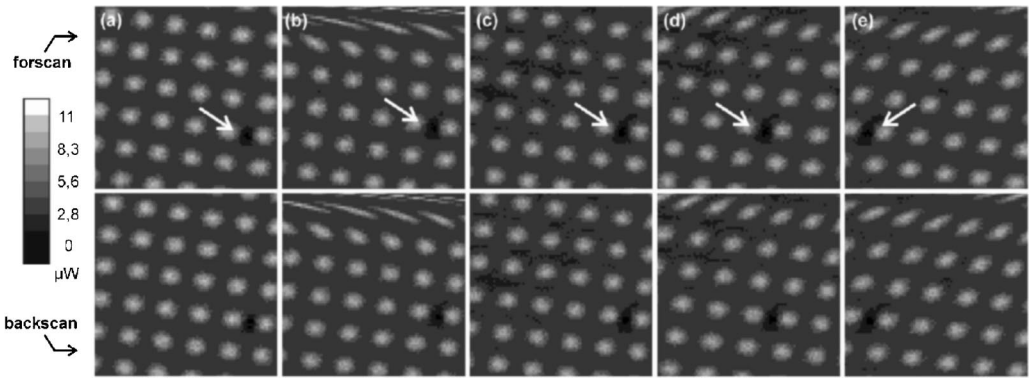


FIG. 4. Slip-stick step-scanning confocal optical images of Al squares (1 $\mu$m$\times$1 $\mu$m) with a 2 $\mu$m period on $SiO_2$ substrate over an area of about 8 $\mu$m $\times$8 $\mu$m. The top row shows images in the forward scan configuration; i.e., lines are acquired from left to right during a step-scan from right to left. The lower row shows images of the corresponding reverse scan with lines taken during the return trip. Every image consists of 80 lines and all images are acquired from top to bottom. (a) Forward (80 pixels/line) and reverse (90 pixels/line) step-scanned images taken with the translation stage in its locked mode. (b) Before the forward and reverse images were acquired again, the translation stage was moved 80 steps to the left. The first lines in the top of both images are very distorted; in the bottom region they are quite similar to the first images. (c) This image was acquired without changing any parameters. It reveals that the feature marked by the arrow is still where it was in image (a), indicating that the step-scanning range came back to its initial position in spite of the 80 extra steps made to the left. (d) The number of pixels for the reverse scans was reduced from 90 to 85. We observed a net shift of the sliding block to the left before locking set in again. (e) A further reduction of the backwards steps to 80 pixels/line shifted the sample further to the left. Changing the number of reverse scan pixels thus allows us to controllably shift the locked-mode region in slip-stick step-scanning imaging. The incident laser power we used in this experiment was 140 $\mu$W, the maximum scattered laser power was about 10 $\mu$W, and the reflectivity signal acquisition time was about 1.2 $\mu$s per pixel.

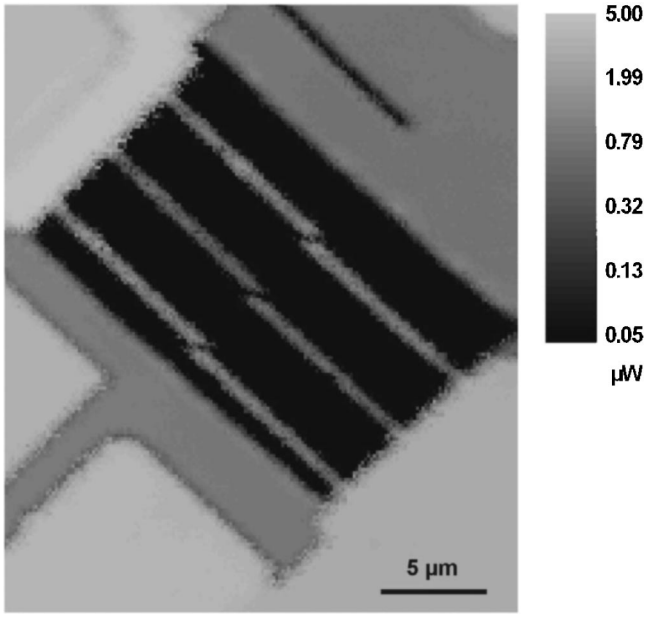


FIG. 5. Slip-stick step-scanned confocal optical image of three pairs of silicon nanocantilevers freely suspended above a rectangular hole aperture. Each cantilever (10 $\mu$m long, 120 nm thick, 200 nm wide) faces another one, forming a pair with their free ends separated by 200 nm. The image was taken using 180 by 180 steps of 12 V, each with a reflectivity signal acquisition time of 60 $\mu$s per pixel. The incident laser power was about 40 $\mu$W.

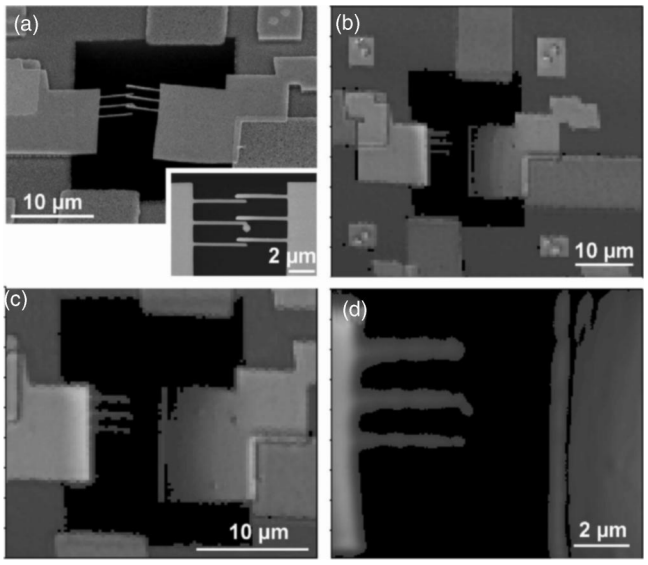


FIG. 6. Scanning electron micrographs and scanning confocal images of a sample containing six freely suspended silicon nanocantilevers (4 $\mu$m long and 200 nm wide). (a) The scanning electron micrograph oblique view of the sample is our reference image. The inset shows the top view of the cantilevers. (b) The slip-stick step-scanning confocal optical image shows no distortion in the image when compared to the SEM, apart from the "missing" cantilevers on the right that are out of focus, leading to an exclusion of their scattered light by our confocal setup. By reducing the amplitude of the voltage pulses on the PZT actuator from 24 V down to 18 and 7 V, respectively, zooming in is possible, as shown in (c) and (d). Three fingers can be clearly resolved, along with the particle that sticks to the middle cantilever, as seen from the SEM. The scans in (b) and (c) contain 100 by 100 pixels and a reflectivity signal acquisition time of 15 $\mu$s per pixel. Image (d) contains 200 by 200 pixels with an acquisition time of 150 $\mu$s per pixel.

gate. This is illustrated in Fig. 2. Against all expectations, we also found out that a subsequent small change of the number $M$ of backward steps did not change the image at all. Larger changes in $M$ resulted in a net shift of only the image position.

The absence of distortions in the images such as seen in Fig. 2 necessitates that for each line, the translation stage of the fast axis made it back to its initial position after having done the return trip. If this were not the case, a small systematic error would add up, leading to a remarkable distortion of the image. For purpose of illustration, let us assume a systematic difference between the size of a forward and a reverse step of only 1%. Assuming now that a line in the image consists of 100 pixels, this would result in a net loss of one step per line. Consequently, every linear feature on the sample perpendicular to the scanning axis should appear bent to 45°. Scanning for the first time over the sample confirms this picture at first. In Fig. 2(a) the first few lines in the top of the image appear highly distorted; in this regime every horizontal line is shifted with respect to the previous one. Surprisingly, after a few lines (typically about 10–20 lines, sometimes up to several hundreds) the distortion in the image disappeared as if the systematic difference in the forward and reverse scan length was exactly cancelled. In this mode, the slip-stick step-scanning locked into a new regime of self-correction that was not at all expected. As a result, the sample's structures became clearly visible in the lower part of Fig. 2(a). Such a behavior was found in all of the translation stages we used. In all cases, the locking behavior once obtained was rarely lost again. A second scan over the same area always started directly in the locked mode, as can be seen from Figs. 2(b) and 2(c). In case the system did not lock within the first few lines, adjusting $M$ speeded up the process. We tested more than 20 stages with different sizes and manufacturing methods, indicating that the locking effect has little to do with the details of the engineering of the stages but is instead dominated by the nature of the friction involved in the slip-stick motion. Still, it is very important to machine the rod and the v-grooves with high mechanical accuracy to ensure a planar good frictional contact.

The beauty of this effect is that once the slip-stick scanning engages in its locked mode, it is very robust against any drift and can be repeated over and over without any noticeable change. As seen in Fig. 3, a single line scanned by the fast axis in its locked mode without moving the slow axis remains nearly unchanged after 1000 scans. For this rather typical case, we evaluated that the shift in position after a scan of 60 000 pixels is less than 0.005%. However, the advantage of locking into a self-correcting scanning regime could turn into a disadvantage since it makes it difficult to take an image at a slightly shifted position, as seen in Fig. 4. Our attempts to displace the imaged region by stepping the translation stage to a different position prior to a new scan led to exactly the same image, apart from the first few lines, as illustrated in Fig. 4(b). In other words, the scanner has a memory and locks into a stable scanning mode immune to the changes we were trying to impose. Although we profit greatly from the stability of this effect, we have not yet understood the mechanism that provokes it. We speculate that it

finds its root in a self-organization in the structure of the solid-state lubricating medium between the faces of the guiding rods and the v-groove faces in the sliding block. Experiments are planned to investigate the role of the lubricating medium. It is worth pointing out that this effect survived down to cryogenic temperatures as low as 50 mK and in ultrahigh vacuum.

To make it possible to take an image at a slightly different position, we found a way to temporarily overcome the locking. In Figs. 4(d) and 4(e) we show that reducing the number $M$ of steps in the reverse scan while keeping the number $N$ of steps in the forward scan constant led to a small shift in position (see arrows). A variation of the number of steps back led initially to a few distorted lines before the translation stage locked into a new shifted range of the self-corrected scanning regime. By a variation of the number of reverse steps, it was possible to image every area we wanted to. Also remarkable is the counterintuitive observation of locking for different $M$ at fixed $N$ with $M$ varying by 10% and more.

### B. Slip-stick imaging of individual structures

In contrast to the imaging of periodic patterns, for the imaging of single and small structures an adjustment of the scanning region to a certain area is necessary. The proof that this can be done is shown in Fig. 5. It depicts a scanning confocal image of a freely suspended nanostructure consisting of cantilevered beams that are 10 $\mu$m long and 200 nm wide. The resulting image is a convolution of the optical spot shape and the sample, making the cantilevers look wider than they really are. The height and width of the confocal optical image had to be calibrated by adjusting the optical image to that taken with a scanning electron microscope (SEM). Height and width were adjusted independently, since the step sizes of the two step-scanning axes were different. It can be seen from the image that the steps of the slip-stick positioner are quite uniform and the imaging is very linear. In contrast to ordinary piezo scanners, our system was able to scan a rather large area without significant image deformation.

A reduction of either the total number of steps or the size of a single step led to images of smaller areas. By combining smaller areas with a shift in position, it was possible to zoom into a specific region. Due to the locking to the region that had been scanned before, the zooming had to be manually assisted. If a drift back to the previous site occurred, the number of steps in the opposite direction was enhanced just until it overcompensated the drift. This kept the new position stable, and after about 10 to 100 lines of scanning, locking set in at the new site. Once stabilized, the new position was observed to be as stable as the previous one. We demonstrate the zooming feature in Fig. 6.

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