A compact nano-positioning stage with high vibrational eigenfrequencies

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Abstract

A compact nano-positioning stage is described that has high vibrational eigenfrequencies and is, therefore, insensitive to external vibrations. The high eigenfrequencies are produced by a rigid structure that is designed so that it does not degrade the motional performance of the stage. Preliminary performance evaluations are presented. We describe how a positioning stage of this type could be used as an integral part of a proximal probe.

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I. INTRODUCTION

The physical sciences are rapidly converging on the control of materials, devices and sensors at the atomic and molecular level\textsuperscript{1,2}. This endeavor depends critically on the existence of positioning stages in applications such as sensing, imaging or lithography that have sub-nanometer spatial resolution. Although, there are a wide range of positioning stages in use, inertial sliders that utilize piezoelectric actuators have become ubiquitous\textsuperscript{3–11}.

One example of an inertial slider based upon piezoelectric tube actuators is the Besocke-beetle\textsuperscript{12}, which is a popular choice for scanning tunneling microscopes (STMs); the beetle geometry offers first-order thermal compensation, good positioning performance, and excellent ease-of-use. However, compared with tube scanners, the eigenfrequencies of beetle-type STMs are actually quite low. In fact, it is a common misconception that the small size of beetle-type STMs produces high eigenfrequencies and good vibrational stability. The reality is that although the mass of a beetle is small compared with many other inertial sliders, the lowest eigenfrequency of the beetle lies below the bending mode of a typical tube scanner\textsuperscript{4,13–16}. This makes the beetle more sensitive to external vibrations.

Can the lowest eigenfrequency of beetle-type STMs be increased? We have shown previously that they can\textsuperscript{13,17,18}. Without modifying the conceptual design, beetles can be built with stiffer piezolegs. This can be achieved either by increasing the diameter of the tube, increasing the tube wall thickness, reducing the length or some combination of these three approaches. Unfortunately, stiffening the legs adversely affects the motional performance, because higher voltages must be applied to the legs to get the same range of motion. Consequently, if the same voltage waveforms are used to move the stiffened beetle, the steps will be smaller and there will be concomitant reduction in the the course approach speed. Can the rigidity of this type of inertial slider be increased in some other way? And can this be done without affecting the speed of the inertial slider? We have found a solution to this design problem. In the remainder of this paper, we describe a very rigid nanopositioning stage (nPS) that has motional performance comparable to that of a beetle-type inertial slider.
II. DESIGN

Figure 1 shows a photograph (a) and a schematic rendering (b) of the nPS. A rigid structure is constructed by gluing three aluminum bars to four cylindrical piezoelectric tubes. Compared with beetle-type inertial sliders it has a very low profile, standing only \( \sim 1.4 \) cm high. The prototype was \( \sim 4.5 \) cm long and \( \sim 1.5 \) cm wide in order to accommodate the dimensions of our sample holders. If required, the profile could be lowered further by mounting the wire connectors to the side of the aluminum bars. The wire connectors that are mounted to the central bar connect to a tip holder that was installed in the prototype stage (see later).

A. Piezotube Arrangement

In contrast to beetle-type inertial sliders, the piezoelectric tubes are horizontally mounted. A schematic of the piezotube arrangement is shown in Figure 2. All tubes are made from PZT-5A material and are 1.27 cm long, with 0.32 cm outer diameter (OD) and 0.06 cm wall thickness. The central aluminum bar is supported solely by the
FIG. 2: Top (a) and side (b) views detailing the piezotube and wiring layout. With the electrodes wired in parallel, and with appropriate signal summing, the number of control wires is reduced to four. In order to achieve displacement in the $y$-direction with electrodes wired in parallel, the piezotubes on each side of the centre piece were oppositely polarized (b). Fine and coarse movements are performed using the same actuators.

piezotubes (Figure 2b). It does not make contact with the walking surface. One end bar contains four control wire connection sockets, and it is supported by two spherical ruby feet. The other end bar has no wire connections and it is supported by a single ruby sphere, completing a stable tripod geometry.

Directions are defined to be consistent with other beetle designs in our laboratory; $+x$ is the direction of sample approach (perpendicular to the long axis of the nPS), $+y$ is parallel to the long axis, and $+z$ is upwards. Coarse movement is achieved by moving the stage in either the $x$ or the $y$ directions. Fine movement of the central bar, relative to the outer two bars, is also possible in all three orthogonal directions ($x$, $y$ and $z$).

B. Wiring and Motion Control

The aluminum parts are electrically interconnected by wrap-around electrodes on the inside of each piezotube. The ground wire connection is made to a socket directly attached
to the central aluminum bar, grounding the entire chassis of the nPS. Each tube has identical equally-spaced quadrant electrodes on its outer diameter. The four electrodes on each tube are wired in parallel, reducing the total number of control wires to only four. Figure 2 also shows the wiring scheme for these electrodes.

Macroscopic motions are made using inertial sliding. Motion in the $x$-direction is produced by applying appropriately polarized control signals to the side electrodes as shown schematically in Figure 3a. Similarly, motion of the central bar in the $z$-direction is produced by applying signals to the top and bottom electrodes. Provided the signal does not contain large and rapid voltage changes, the central aluminum bar will flex in the $x$ (or $z$) direction and the feet will not move relative to the surface. However, if the piezotubes are straightened rapidly by reducing the voltage on the side electrodes to zero, the end bars shift in the $x$ (or $z$) direction, overcoming friction between the feet and the walking surface. It should be clear from Figure 3a that there is a major difference between the nPS and a beetle-type inertial slider. In the latter, the majority of the beetle mass is concentrated on one side of the piezos, in the metal chassis. In the nPS there is mass on both sides of the piezos.

A different technique must be used to control the motion in the $y$-direction. The approach we have adopted is to use piezotubes with opposite polarization on either side of the central bar. Applying a voltage to all electrodes expands the tubes on one side and contracts the tubes on the other, shifting the central bar in the $y$-direction (Figure 3b). Applying a sawtooth waveform to the electrodes produces motion in the $y$-direction as shown schematically in Figure 3b. Changing the polarization direction on half of the piezos also has implications for the control of the $x$ and $z$ motion. For the $x$ and $z$ directions to work correctly with this reversed polarization, the electrodes on either side of the central bar must be wired in the opposite sense. The top electrodes on one side of the nPS must be connected to the bottom electrodes of the other side, and so on (Figure 1a). Moving in the $x$, $y$, and $z$ directions simultaneously is made possible by summing the $Y$ signal into the $X$ and $Z$ signals as shown in Figure 2. Consequently, only five wires are required for full control of the nPS: four control wires ($Y + X$, $Y - X$, $Y + Z$, and $Y - Z$) and a ground wire. Despite this simplification, the signals that drive the piezoelectric tubes for each independent direction are identical to those used for our b1 beetle$^{13,18,19}$. 
FIG. 3: Controlling the motion of the positioning stage in the $x$ and $y$ directions. For motion in the $x$-direction (a), sawtooth waveforms of equal magnitude and opposite polarity are applied to the side electrodes, displacing the stage by $\Delta x$ in each cycle. For motion in the $y$-direction (b), a sawtooth waveform is applied equally to all electrodes, displacing the stage by $\Delta y$ in each cycle.

C. Vibrational Properties

The small mass of the central piece raises the lowest eigenfrequency of our prototype to close to 15 kHz. A beetle with similar piezotubes and comparable overall dimensions will have a lowest eigenmode of less than 2 kHz. In the beetle design, the mass supported by
the three piezotubes is large (>10 g) since it must be wide enough for the tripod, and it must carry the weight of the scanner, and all of the wiring and connections. In contrast, the nPS central mass is only ~0.53 g. This prototype was constructed with a tip holder and tip built into the central aluminum bar. Removal of the tip holder would reduce the mass and shift the eigenfrequencies even higher.

The outer electrode quadrants do not extend the full 1.27 cm of the tube length due to the wrap-around inner grounding electrode. The active part of the tube is about 0.85 cm long. If the inactive portion of the tube is left unstiffened, the entire tube can bend under external excitation, resulting in a resonant mode of 8.7 kHz. With this in mind, the piezotube were mounted to posts which fit snugly into each end of the tube to a depth of about 0.2 cm. Therefore the tube can bend along its usable length only, raising the lowest eigenfrequency up to about 15 kHz.

D. Thermal Matching

The fact that materials expand or contract with temperature changes cannot be avoided, so precautions should be taken to ensure that these changes do not affect tip-sample separation when the stage is used as a scanning probe. Proximal probes require position control on the order of Ångstroms, so even small temperature changes can adversely affect scanning performance due to differential thermal contraction.

One aspect of design in which the beetle excels is thermal matching. Consider the geometry of a beetle-type STM: a tripod supports a central chassis which in turn supports a scanner. There are two vertical paths that can be taken from the surface to the beetle chassis. The first follows the legs of the tripod from the walking surface to the chassis (leg path), and the second follows the scanner from the sample surface to the chassis (scanner path). If these two paths contain equal lengths of identical materials then the beetle is thermally matched, since temperature-induced changes in path length will also be equal. Choosing suitable materials and minimizing path length is beneficial to scanning probe operation at any temperature.

The nPS design provides good thermal matching and this is essential if the nPS is used as an integral part of a proximal probe. It has a very low profile, and thus has a significantly shorter path length than a standard beetle. To be thermally matched, both
the feet and tip should be made from the same material; tungsten is a viable option. Therefore, with careful material choices, the nPS is suitable for both fixed and variable temperature applications.

III. PERFORMANCE

A. Speed and step size

We will now quantify the motional performance of the positioning stage with the results of preliminary tests. The main quantities of interest are the speed and step size, both of which were examined as a function of applied voltage and frequency.

To measure its speed and step size, the nPS stage was placed on a level, polished surface, and it was driven by a standard sawtooth approach waveform produced by a STM controller (RHK Technology). The time taken for it to travel a distance of \( \sim 1 \) mm to \( \sim 4 \) mm was measured using a stopwatch and traveling microscope. An average speed was calculated from the distance traveled in the measured time. Step size was calculated assuming that the nPS made equal steps for each cycle of the waveform. The results for the \( y \)-direction are summarized in Figure 4. Measurements for the \( x \)-direction followed similar trends.

First, the applied voltage was varied while the frequency of the approach waveform was fixed at 2.5 kHz. It is expected from the Equations 1 and 2

\[
\Delta x = \Delta z = \frac{4\sqrt{2}d_{31}VL^2}{\pi(D_O + D_I)t} \\
\Delta y = \frac{d_{31}VL}{t}
\]

that both speed and step size will vary linearly with applied voltage. Here, \( \Delta x, \Delta y \) and \( \Delta z \) are the piezotube deflections in the \( x, y, \) and \( z \) directions respectively. \( d_{31} \) is the piezoelectric strain constant (-1.73 Å/V for PZT-5A), \( V \) is the applied voltage, \( L \) is the length of the tube, \( D_O \) is the outer diameter of the tube, \( D_I \) is the inner diameter of the tube, and \( t \) is the wall thickness of the tube. Our measurements confirm this linear relationship (Figures 4a and 4b). The linear trend should extrapolate to higher voltages,
FIG. 4: Speed and step size for the nPS in the $y$-direction under various conditions. (a) and (b) show the speed and step size respectively as the applied voltage was varied at a frequency of 2.5 kHz. (c) and (d) show the speed and step size respectively as the frequency was varied at an applied voltage of 105 V.
but 105 V is the maximum unsaturated output limit of the RHK controller. At voltages lower than 50 V, the inertial sliding technique became unreliable due to excess sticking.

Next, the frequency was varied while the applied voltage was 105 V. The plot in Figure 4c confirms the expected linear relationship between speed and frequency. It is clear that above about 2.5 kHz, strong deviations occur, corresponding to excess slipping. Similarly, frequencies lower than 1 kHz gave rise to excess sticking. Similar results were obtained for the $x$-direction. However, motion in the $x$-direction is particularly sensitive to surface conditions due to the large separation and asymmetry of the feet placement in the prototype. Twisting sometimes occurred over the large displacements used for these tests. The prototype was made long so that it could work with our current sample holders, but this makes it more susceptible to twisting. The issue could be remedied easily in a second prototype by shortening this dimension – a reduction by $\sim 50\%$ would be possible with no major design changes. Reducing the nPS dimensions even more to a square is possible.

Figure 4d confirms that the step size remains constant as the frequency varies (frequency of deflection does not affect the magnitude of the deflection). Again, the results outside of the range 1 kHz to 2.5 kHz were inadmissible. At this voltage (105 V), the step size is $11 \pm 3$ nm in the $x$-direction, and $36 \pm 3$ nm in the $y$-direction. It is interesting to note that the $x$-direction step size is consistently smaller than the results for the $y$-direction (also true for speed). Typically, perpendicular ($\Delta x$) deflection of a piezotube is approximately four times larger than parallel ($\Delta y$) deflection. However, the arrangement of the piezotubes in the nPS adds an inherent stiffness, limiting their deflection in the $x$-direction.

Under the testing conditions, the maximum speed of the nPS is about 5 mm/min. Although this is slower than Klocke Nanotechnik’s Nanomotor ($\sim 100$ mm/min) and also our standard $b1$ beetle ($\sim 50$ mm/min), it is significantly faster than our stiffened $b3$ beetle ($<1$ mm/min)\textsuperscript{13,17} and in a range that is well suited for practical applications that require nanometer spatial resolution.
FIG. 5: The measured nPS resonance spectrum suggests that the vertical bending mode (\(\perp\uparrow\)) is at 13.6 kHz, and the horizontal bending mode (\(\perp\leftrightarrow\)) at 15.1 kHz. The rotational or tortional mode (\(\theta\)) for the centre brace rotating about the long axis of the nPS is 21.1 kHz.

B. Vibrational Performance

Vibrational spectra of a standard beetle (\(b1\)) and a stiffened beetle (\(b3\)) have been measured previously\(^{13,17}\) to compare the relative stiffness of the two designs. In these studies, a 10 V p-p sinusoidal waveform was supplied to the +X electrode of the scanner, and a lock-in amplifier was used to monitor the electromechanical pick-up response from the +X electrode of the piezolegs. The frequency of the sinusoidal waveform was varied to measure the vibrational spectrum of the beetle. Due to the simplicity of the nPS this connection strategy is impossible to implement. However, this was not a insurmountable obstacle. Instead, a 3 V p-p sinusoidal waveform was applied to its Y+X electrodes, and the response from its Y-X electrodes was monitored. The vibration spectrum for the nPS is shown in Figure 5 for the frequency range from 0.1 to 25 kHz. The following control experiment was also performed with the \(b1\) and \(b3\) beetles to check that this strategy would produce meaningful results. The same 3 V p-p signal was applied and measured using the +X and -X leg electrodes respectively. Results obtained using this modified stimulation method were equivalent to the original results, and since the stimuli were identical, these results can be used in direct comparison with the vibrational response of the nPS.
We have previously\textsuperscript{13,17,18} used simple models to calculate beetle eingenfrequencies based on the known eingenfrequencies of a massless hollow tube\textsuperscript{4,14–16}. To confirm that this simple treatment provides the correct physical picture of the eingenmodes we have used a finite element analysis using the SAP2000 software package\textsuperscript{21}. The model of the nPS consisted of approximately 100 elements, each of which spanned a length of approximately 1 mm. An eigenvector analysis was performed, identifying the undamped modes of vibration. The boundary conditions fixed the feet in both translation and rotation about all three spatial axes. While large amplitude low frequency oscillations involving translation of the feet across the surface are possible, they have not been observed in practice\textsuperscript{13}. Similarly, comparing the calculated eigenfrequencies, for the case when rotation is allowed, with the measured eigenfrequencies suggests that rotation of the feet is negligible. Consequently, we believe that the boundary conditions that we have used are valid.

Using the FEA model we were able to identify the modes associated with the lowest eigenfrequencies. The lowest mode, shown in Figure 6a, consists of the central bar oscillating vertically and will be referred to as the vertical bending mode ($\bot\uparrow$). The next mode, the horizontal bending mode ($\bot\leftrightarrow$), is a result of horizontal oscillations of the central bar (Figure 6b). The third mode, referred to as the torsional mode ($\theta$), consists of the central bar rotating about the long axis of the nPS (Figure 6c).

Next, estimates of the eigenfrequencies were made using the eigenfrequency of a massless hollow tube\textsuperscript{4,13–16}

$$f_\bot = \frac{1}{2\pi} \sqrt{\frac{\kappa_\bot}{m_l}}. \quad (3)$$

The spring constant associated with the bending excitation is:

$$\kappa_\bot = \frac{3\pi}{64} E \frac{D_O^4 - D_I^4}{L^3}, \quad (4)$$

and the eigenfrequency of the torsional mode can be obtained from the eigenfrequency of the bending mode using the following approximate relationship:

$$f_\theta \approx \sqrt{2} f_\bot. \quad (5)$$

Coincidentally, this approximate relationship between the eigenfrequencies of the torsional
FIG. 6: Schematics of the modes of vibration for the nPS. (a) is the vertical bending mode (\( \perp \)), (b) is the horizontal bending mode (\( \perp \leftrightarrow \)), and (c) is the torsional mode (\( \theta \)). Dark lines represent the deformed shape, lighter gray lines represent the undeformed shape, and the crosses indicate the positions of the feet.

and bending modes is also found in beetle-type STMs\textsuperscript{16}. For beetle-type STMs the moment of inertia of the chassis can be approximated by the moment of inertia of a solid disk or cylinder, so it is not obvious apriori that the torsional and bending eigenfrequencies of the nPS should be related in the same way. We found that it was important to accurately model the distribution of mass in the central bar. For example, if we (erroneously) assumed that the central bar is simply a uniform rod, then the torsional eigenfrequency \( f_\theta \) shifts upwards to \( \approx \sqrt{3} f_\perp \) in disagreement with experiment (Table I). Ultimately, the central bar of the nPS was represented by a combination of two cylindrical rods and a rectangular block. The derivation was modified to also reflect this geometry and that the nPS contains four piezotubes rather than three. A detailed description is included in the Appendix.

In Equations 3 to 5, \( m_l \) is the mass loading the tube and \( E \) is Young’s modulus of
the tube. The other parameters are as introduced previously. The results obtained with Equations 3 and 5 are indicated in Figure 5 and are listed in Table I. The mass used in the calculations was 0.133 g, which is one quarter of the total mass of the centre portion of the nPS (assuming uniform distribution across all four tubes).

These equations do not make a distinction between the two possible bending modes (⊥ and ↔) of the nPS structure as indicated by the FEA model. The arrangement of the piezotubes increases the structural rigidity of the nPS in the horizontal direction, but not in the vertical direction. It is therefore expected that the vertical mode frequency is lower than the horizontal mode frequency. The spectrum in Figure 5 shows a peak as expected at 15.1 kHz for the horizontal mode, as well as a distinct peak at 13.6 kHz which is attributed to the vertical bending mode. The torsional mode is observed at 21.1 kHz. Peaks observed above 22 kHz are attributed to the nPS’s wire connections, as confirmed by the following control experiment. With the nPS placed in a fixed position, vibrational responses were obtained after subjecting the nPS wire connections to various adjustments including twisting, loosening and/or changing the connector, as well as adding extra wires. It was observed that the spectra remained unchanged between trials except for the region above 22 kHz, where significant variations appeared. Obtaining multiple spectra without altering the connections at all between trials showed good repeatability across all frequencies.

Aside from the identified peaks, the response of the nPS is quite flat. Its lowest resonant mode of the nPS is 8 times greater than the standard b1 beetle, and 1.3 times greater than the stiffened b3 beetle. The spectra are plotted in Figure 7 for the range below 5 kHz, and it is clear that the vibrational response of the nPS is suppressed to a much greater degree than both beetles. The vibrational stability of the b3 beetle is a substantial improvement
FIG. 7: Comparison of the nPS vibrational spectrum with the standard (b1) and the stiffened (b3) beetle-type microscopes.

over the b1 beetle; however, the ability of the b3 beetle to move was severely affected by its stiffness. It is evident from the figure that the nPS response is better than the b3 response; it is essentially constant for the range shown. This is a significant achievement considering that the motional performance was not significantly compromised to achieve the greater stiffness.

IV. THE POSITIONING STAGE AS AN INTEGRAL PART OF A PROXIMAL PROBE

We believe that a proximal probe could readily be integrated into the positioning stage and, as mentioned earlier, our prototype was built with an STM tip installed. We are currently testing to see if the drive piezos on the nPS could also be used as scanner piezos. In our beetles, the signals sent to the scanner for fine tip positioning are referred to as scan signals (subscript "s"), and the signals sent to the leg piezotubes for coarse tip positioning (including macroscopic positioning) are called offset signals (subscript "o"). For the nPS to function as an STM, the scan signals must be combined with the offset signals. The geometry of the piezos also requires that the y-signal is sent to each peizo concurrently. The four overall control signals for full STM functionality, as labeled in Fig. 2, are given in Table II.
TABLE II: Control signals required for full STM functionality. The sector labels are as indicated in Figure 2.

<table>
<thead>
<tr>
<th>Sector Label</th>
<th>Applied Voltage</th>
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<tbody>
<tr>
<td>$Y + X$</td>
<td>$Y_o + Y_s + X_o + X_s$</td>
</tr>
<tr>
<td>$Y - X$</td>
<td>$Y_o + Y_s - X_o - X_s$</td>
</tr>
<tr>
<td>$Y + Z$</td>
<td>$Y_o + Y_s + Z_o + Z_s$</td>
</tr>
<tr>
<td>$Y - Z$</td>
<td>$Y_o + Y_s - Z_o - Z_s$</td>
</tr>
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Thus moving the tip by concurrently displacing the four leg piezos is clearly different, although not more complex than displacing a single tube scanner, and consequently the nPS requires non-standard control electronics. This does not make motional control more difficult to achieve, but it does mean that the nPS is not presently compatible with many standard commercial controllers due to the limited versatility of the signal summing hardware. Custom electronics are currently being built to test the stage.

Acknowledgments

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Appendix

The simple relationship between the torsional mode and the bending mode has been derived previously for the beetle\textsuperscript{16}. The derivation presented here follows the same strategy, but makes the necessary modifications to account for the unique geometry of the nPS.

The moment of inertia of the central bar about the torsional axis was calculated by separating it into three simpler components as shown in Figure 8. The first two pieces are identical cylindrical rods of radius $r$, each displaced from the rotation axis by distance $d$ (these are the mounting posts for the piezotubes). The radius of the rods is $\approx 1/7d$, \textit{etc}.
FIG. 8: A simplified representation of the central piece of the nPS consisting of two rods and one rectangular block.

and the mass of a single rod, $m_{rod}$, is $\approx 1/8 m_{total}$, where $m_{total}$ is the total mass of the central piece. The third component is a rectangular block of length $2d$ and thickness $2r$. While the centre portion of the block is actually hollowed and not of uniform thickness, the overall mass distribution close to that of a solid bar when all internal components are included. The mass of the block, $m_{block}$, is $3/4 m_{total}$.

The moment of inertia for a rod can be found using the parallel axis theorem, and writing the parameters in terms of only $m_{total}$ and $d$:

$$I_{rod} = \frac{1}{2} m_{rod} r^2 + m_{rod} d^2 \approx \frac{1}{8} m_{total} d^2. \quad (6)$$

Similarly, for a rectangular block of length $2d$ and thickness $2r$:

$$I_{block} = \frac{1}{12} m_{block} \left( (2r)^2 + (2d)^2 \right) \approx \frac{1}{4} m_{total} d^2. \quad (7)$$

The total moment of inertia is simply obtained by summing the individual moments for two rods and one block. However, it is more useful to write it in terms of the mass loading each of the piezotubes, $m_l$, which is, assuming equal distribution across all four piezos, $1/4 m_{total}$:

$$I_{total} = 2 m_l d^2. \quad (8)$$

The torsional spring constant can be adjusted to account for the fourth piezotube:

$$\kappa_\theta = 4 \kappa_\perp d^2, \quad (9)$$

where $d$ is the mounting radius of the piezotubes. Finally, the angular frequency of the
torsional mode is:

$$\omega_\theta = \sqrt{\frac{K_\theta}{I_{\text{total}}}} = \sqrt{2}\omega_\perp$$

(10)

which, coincidentally, is identical to the expression that was derived previously for the 
beetle$^{13,16}$
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