Characterising performance of TEM compatible nanomanipulation slip-stick inertial sliders against gravity

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Abstract. Slick-stick inertial sliders have been used in the manufacture of a novel miniaturised nanomanipulation and nanoindentation system. This has been designed to perform sub-micron localised in-situ deformation studies in a high resolution transmission electron microscope (HRTEM). Coarse position is realised by three independent sliders which are set mutually perpendicular to one another (x, y and z) with a range >1mm and resolution <100nm. In this paper we discuss the effect that gravity has on the performance of the nanomanipulation slip-stick inertial drives by monitoring displacement rate, resolution and the effect of the normal force across the slip-stick slider. We report on the successful actuation of slip-stick sliders operated in a vertical orientation.

1. Introduction
The interest in miniaturisation and nano-science leads to the increasing significance of understanding mechanical properties and contacting materials at the nano-scale. Processes such as local bonding at contact sites and deformation are extremely important when trying to understand materials wear and degradation at such a scale.

A range of experimental techniques including nanoindentation and atomic force microscopy (AFM) have been successfully used to determine nano-scale mechanical properties [1]. These techniques however are limited in their approach and do not address the importance of microstructural changes during mechanical loading. To overcome this issue, more recent experimental techniques have combined nanoindentation or scanning tunneling microscopy (STM) with microstructure imaging by transmission electron microscopy (TEM). This has been successful in beginning to combine local mechanical testing with real-time microstructure evolution [2-5].

The combination of nanomanipulation and contact testing with TEM imaging generates its own problems. To avoid major modifications to the TEM, the positioning hardware must fit within a standard sample holder assembly. It is for this reason that small slip-stick inertial sliders [6] have been used to develop a nanopositioning/nanoindentation system and a three-axis positioning drive has been built. Previous work has used piezoelectric tubes to achieve displacement along vertical axes [7-8] however; limited size and volume have previously not been a critical issue of design.

2. Nanoindenter design
The entire nanopositioning system is designed to fit inside a bespoke hollowed out specimen holder for a JEOL (Japan) 2010/3010 series instrument. The developed nanopositioning/nanoindentation
system consists of a three-axis slip-stick inertial slider mechanism set in a Cartesian geometry (x, y and z). The three axes of the coarse positioning drive are completely independent, and each drive is designed to achieve a displacement >1mm and step resolution <100nm. Along the indentation axis (z) the displacement range is designed to be up to 6mm to allow the indenter tip to be brought towards the sample through a large separation distance which allows simple sample mounting. The vertical-scan axis (y) is restricted in displacement to <1.5mm to prevent any part of the positioning system colliding with either pole piece within the TEM column which is separated by a gap of 2.1mm (JEOL 2010F).

Slip-stick inertial sliders have been used similar to that shown in Figure 1a based on a piezoelectric shear plate. This type of actuation device requires simple control electronics to generate the applied signal in Figure 1b. It is this shaped waveform that generates the piezoelectric shear motion and slip-stick movement shown in Figure 1c once correct normal force \( N \) has been applied across the contacting slider junction.

![Figure 1](https://example.com/fig1.png)

**Figure 1.** a) Schematic of an inertial slider. \( N \) is the normal force applied to the sapphire/alumina contact plane. The ball will slip against the alumina plate if the inertial and external forces are greater than the frictional force \( F_e \). b) the applied electrical signal used for actuation and c) the generated motion over a single waveform where \( A \rightarrow B \) shows sticking and \( B \rightarrow C \) shows slipping motion.

3. **Performance characteristics of the Nanoindenter drive**

3.1. Initial drive setup

The performance of each axis mechanism was assessed using optical displacement sensors. Initially each drive was actuated along its entire displacement range to ensure that the clamping force was set normal to the sapphire-alumina contact plane. If clamping was not applied normal to the contact plane the displacement rate was observed to change along the total slider displacement.

It was also observed that during actuation the drive underwent a ‘setting in’ period. At the sapphire-alumina junction wear was observed at the point contact. This occurred until the wear rate of both the sapphire ball and \( \text{Al}_2\text{O}_3 \) sheet was reduced. After running the slider over the total range a number of times the displacement rate settled down to a constant and repeatable value. The applied normal force across the contact junction was also affected by the wearing of the sapphire ball point. As the point was worn away the separation gap of the slider and clamp increased and the slider became less stiff. Once steady motion was observed and the setting in period was completed slight adjustment of the normal force was required to increase the stiffness of the slider.

3.2. Performance testing

The slider displacement was recorded along each axis a number of times until repeatable motion was observed. Previous work by Bobji et al. suggested that a maximum step displacement of 275nm measured by interferometer could be achieved for an identical piezoelectric shear plate [5]. This corresponds to the free displacement of the piezoelectric element with maximum peak voltage applied. To reduce the step size the voltage could be reduced or normal force altered directly affecting the friction \( F_e \). From the maximum step size conditions, adjustment to either reduced or increased stiffness saw a reduction in step size, however for the designed nanoindentation application, increased stiffness
was favoured to prevent the positioning system slipping along the z-axis during nanoindentation tests. A step size of approximately 100nm appropriate for the designed application was achieved.

Table 1 shows the displacement characteristics for both z and x axes measured in their standard horizontal operating orientation. In addition, results are given for the y-axis slider operated in both standard vertical and rotated horizontal orientations. In the drives standard operating orientation both z and x axes have gravitational force acting parallel to the applied normal force and perpendicular to the frictional force. In the vertical slider orientation, gravitational forces act perpendicular to the applied normal force and parallel to the contact plane of the slider.

It can be seen the z and x axes exhibit repeatable displacement in both slider directions and the designed displacement range is achieved. During testing of the y-axis in a horizontal orientation, achieved displacement rate was calculated to be 9.07µm s\(^{-1}\) ±0.01µm s\(^{-1}\) for an applied signal frequency of 125Hz. This rate varies between 8.58µm s\(^{-1}\) and 9.85µm s\(^{-1}\) when operated in its vertical orientation.

Table 1. The observed displacement range and step size of the x and z horizontal coarse axes and the y-axis in vertical and horizontal operating orientations.

| Axis                        | Orientation       | Positive signal applied | Negative signal applied |
|-----------------------------|-------------------|-------------------------|-------------------------|
| z (indentation)             | Horizontal        | 5.5                     | 5.5                     |
| x (scan left & right)       | Horizontal        | 1.5                     | 1.5                     |
| y (scan up & down)          | Vertical          | 1.25                    | 1.25                    |
| y (scan up & down)          | Horizontal        | 1.25                    | 1.25                    |

To ensure the correct force setting and linearity along the y-axis, the entire drive was rotated through 90° so that the y-axis was running in a horizontal orientation with gravitational forces acted parallel to the applied normal force.

When the y-axis was actuated in the horizontal orientation a repeatable step size with minimum displacement rate variation (<±10 nm s\(^{-1}\)) occurred in either direction. During actuation along the correctly orientated vertical y-axis, results showed a variation of step size. Aided by gravity, moving ‘down’, the step size increased on average by 8.16%. During motion opposing gravity, moving ‘up’, the step size was reduced by 6.54% over an average of 10 measured cycles. The measured displacement range and step size in both vertical and horizontal operating orientations can be seen in Table 1.

Figure 2. Piezo actuated test cycles (thin lines) of the y-axis slider showing over an average of 10 cycles (thick lines) a) actuation along the horizontal axis with gravitational force acting parallel to the normal force applied to the slider and b) actuation with gravity acting perpendicular to the applied normal force. A time difference of 7.45s was recorded over an actuation range of 0.5mm for opposing directions in a vertical orientation.
The recorded y-slider motion can be seen in Figure 2 where the variation of displacement rate and step size is shown. Figure 2a demonstrates the linearity and repeatability of the y-axis slider with gravity acting parallel to the applied normal force and perpendicular to the frictional force. Figure 2b demonstrates the effect of gravity acting perpendicular to the applied normal force parallel to the frictional force when the inertial slider drive is operated in a vertical orientation.

4. Discussion

4.1. Overall observations of the nanopositioning system performance

For z and x-axes, where the gravitational force acted normal to the horizontal slider, linear and repeatable motion was observed in both directions. Displacement rate and step size were measured with minimal variation (<±10nm s⁻¹) over the full displacement range.

Variations in step size were seen along the y-axis where the gravitational force acted parallel to the vertical slider axis. The step size and corresponding displacement rate in the ‘down’ direction was observed to be 14.7% greater than the step size in the ‘up’ direction as shown in Table 1.

4.2. Understanding the actuation process

In both the x and z axes, with the addition of the normal force \( N \), the frictional force \( F_e \) was such that \( F_e = f(N + mg) \). For displacement to be achieved the force generated by actuating the piezoelectric material \( F_{\text{piezo}} = k_t\Delta L_o > F_e \) where \( k_t \) is the piezoelectric material stiffness and \( L_o \) is the maximum nominal piezoelectric displacement. In both axes, the level of force required for displacement in either direction was the same.

When gravity acted parallel to the slider as for the y-axis slider, the frictional force was a function of \( N \) only. In this case, the gravitational force \( mg \) either assisted or opposed the actuation generated by the piezoelectric material. Here actuation was achieved only if \( k_t\Delta L_o > F_e \pm mg \) and the reason why asymmetric displacement rates were observed.

To prevent slipping of the vertical y-axis slider whilst no actuation was applied, the friction force must be greater that the gravitational component acting on the slider such that \( F_e > mg \). As the level of friction is directly affected by the amount of normal force \( N \) applied, \( F_e \) can be easily altered.

\[
k_t\Delta L_o > F_e + mg \Leftrightarrow F_e > mg
\]

To prevent the slider from slipping during non operation and achieve actuation in both directions, Equation 1 must be satisfied so that actuation in the ‘up’ direction was achieved.

In summary, we have quantified how miniaturised slip-stick motors constructed from piezoelectric shear plates can be used to produce a displacement in a vertical orientation. The performance of the slip-stick motors were seen to be affected by gravitational forces altering the ~100nm step size by ±8%, however not to a level which hindered the overall performance of the designed TEM nanopositioning system.

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