Dual-stage Thermally Actuated Surface-Micromachined Nanopositioners

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DUAL-STAGE THERMALLY ACTUATED SURFACE-
MICROMACHINED NANOPositionERS

by

Neal Benson Hubbard

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering
Brigham Young University
April 2005
This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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ABSTRACT

DUAL-STAGE THERMALLY ACTUATED SURFACE-MICROMACHINED NANOPositionERS

Neal Benson Hubbard
Department of Mechanical Engineering
Master of Science

Nanopositioners have been developed with electrostatic, piezoelectric, magnetic, thermal, and electrochemical actuators. They move with as many as six degrees of freedom; some are composed of multiple stages that stack together. Both macro-scale and micro-scale nanopositioners have been fabricated. A summary of recent research in micropositioning and nanopositioning is presented to set the background for this work. This research project demonstrates that a dual-stage nanopositioner can be created with microelectromechanical systems technology such that the two stages are integrated on a single silicon chip. A nanopositioner is presented that has two stages, one for coarse motion and one for fine motion; both are fabricated by surface micromachining. The nanopositioner has one translational degree of freedom. Thermal microactuators operate both stages. The first stage includes a bistable mechanism: it travels 52 micrometers between two discrete positions.
The second stage is mounted on the first stage and moves continuously through an additional 8 micrometers in the same direction as the first stage. Two approaches to the control of the second stage are evaluated: first, an electrical input is transmitted to an actuator that moves with the first stage; second, a mechanical input is applied to an amplifier mechanism mounted on the first stage after completing the coarse motion. Four devices were designed and fabricated to test these approaches; the one that performed best was selected to fulfill the objective of this work. Thermal analysis of the actuators was performed with previously developed tools. Pseudo-rigid-body models and finite element models were created to analyze the mechanical behavior of the devices. The nanopositioners were surface micromachined in a two-layer polysilicon process. Experiments were performed to characterize the resolution, repeatability, hysteresis, and drift of the second stages of the nanopositioners with open-loop control. Position measurements were obtained from scanning electron micrographs by a numerical procedure, which is described in detail. The selected nanopositioner demonstrated 170-nanometer resolution and repeatability within 37 nanometers. The hysteresis of the second stage was 6% of its full range. The nanopositioner drifted 25 nanometers in the first 60 minutes of operation with a time constant of about 6 minutes. The dual-stage nanopositioner may be useful for applications such as variable optical attenuators or wavelength-specific add–drop devices.
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Several common machines are designed to place an object in a particular position. A tower crane moves building materials around a construction site (Figure 1.1). A milling machine moves a rotating tool over a part to cut it to a desired shape (Figure 1.2). A read/write head in a hard disk drive moves radially along a rotating platter as it follows a data track (Figure 1.3). Positioning devices such as these move objects too large or too small for a person. They improve accuracy in critical applications and reduce the monotony of handling thousands of similar objects. Positioning tasks that humans can perform are often accomplished more quickly with a machine.

Three significant characteristics of a positioning device are the number of degrees of freedom (DOF) it controls and its range and resolution in each degree of freedom. The controlled degrees of freedom may include any combination of the three translations (x, y, and z) and three rotations (θ_x, θ_y, and θ_z) in the Cartesian coordinate system.

The range of a positioning device is the largest distance through which it can move an object. The smallest controlled movement it can make is its resolution. The accuracy is
Figure 1.1  Tower crane

Figure 1.2  Milling machine
the magnitude of the difference between the desired position and the actual position. The ratio of the range to the resolution is a relative measure of accuracy. With this ratio it is possible to compare the quality of positioning devices of widely different sizes.

The tower crane has three degrees of freedom (Figure 1.1). It can move a steel beam 90 m through the air to within 25 mm of the place where it connects to a structure [1]. The tool on the milling machine can travel at most 876 mm in its three degrees of freedom, but its resolution is 25 µm (Figure 1.2). The hard disk drive reader only needs to control one degree of freedom (Figure 1.3). It has a range of 22 mm and a resolution of 500 nm [2]. The range-to-resolution ratios of the crane, mill, and disk drive are 3600, 35 000, and 44 000, respectively.
1.1 Nanopositioning Systems

Hard disk drives are continually challenged to increase their data storage capacity while minimizing their size. The increase in track density has required the read/write head to move more accurately. Many devices in optical communication, microscopy, and integrated microelectronics are similarly challenged to control position with accuracy as small as a nanometer.

A nanopositioning device moves an object to within a few nanometers of a desired position. A device that is accurate to within a few micrometers is termed a micropositioner. Nanopositioning is not as simple as scaling down a drive screw [3]. It requires new approaches and technologies to eliminate friction and generate appropriate forces. The stipulation of nanometer accuracy implies that the actuator cannot have hinges or bearings because the clearances between parts introduce backlash. Compliant mechanism technology is a key solution to the problems of friction and backlash because it allows mechanisms to be designed without prismatic or sliding joints.

An actuator generates the force required for motion. It is attached to a reference frame and applies a force to an output frame. Most actuators have one degree of freedom. Multiple actuators may be kinematically linked to control more degrees of freedom, including translations and rotations.

Actuators grounded on the same reference frame comprise a single stage. A second stage, or stacked actuator, is one whose reference frame is the output of another, primary actuator. The second stage can control the same degree of freedom as the first stage or a different one, as is illustrated in the following sequence of figures. The two actuators in
Figure 1.4 Actuator configurations: (a) two DOF, one stage; (b) two DOF, two stages; (c) one DOF, two stages

Figure 1.4a control two orthogonal degrees of freedom for the same output frame; they form a parallel kinematic mechanism. In Figure 1.4b, one of the actuators is placed on a secondary frame so that the two degrees of freedom are controlled by separate stages; this is a serial kinematic mechanism. This configuration is often employed in positioning systems to reduce cross-talk between the two degrees of freedom. Figure 1.4c shows two stages controlling the same degree of freedom. In some applications, it is advantageous to control motion in multiple stages. The first stage may have a long range and move an object to approximately the desired location while the second stage attains the required accuracy. This is one way to achieve a large range-to-resolution ratio.

Feedback control is often an integral part of a positioning system. It allows the positioner to reach its goal more quickly and to compensate for disturbances. A control system includes a sensor that measures the position of the object and a processor (analog or digital) that produces the control input. The input is modified such that the device achieves the desired position.
1.2 Microelectromechanical Systems

Microelectromechanical systems (MEMS) combine “one or many micromachined components” that “often integrate smaller functions into one package” and “enable higher level functions” in a larger system [4]. This new class of machines has grown into a wide variety of commercial applications including accelerometers, pressure transducers, and ink-jet print heads [4,5].

MEMS have attractive economic advantages over macroscopic devices. First, MEMS are smaller; they fit in compact packages and allow other parts of an assembly to be smaller. Replacing macroscopic components of a system with MEMS components may reduce the size and weight of the system. Second, there are cases in which MEMS components have lower replacement costs because they are more reliable. Greater component reliability means less maintenance time for the entire system.

Surface micromachining is one technology used to produce MEMS [5,6]. Parts are created in layers; they stack together to form machines. The details are explained in Section 2.4. Surface micromachining originated with the integrated circuit industry and has been modified to produce better mechanical parts. For example, the thicknesses of the layers were increased. Surface micromachining allows mechanisms to be fabricated with smaller features than are possible with conventional machine tools. Large numbers of MEMS chips can be created simultaneously at a low unit cost. This represents a third economic advantage that makes MEMS a competitive technology for the production of mechanical devices.
1.3 Research Objective

This research project tests the hypothesis that a dual-stage nanopositioner can be created with MEMS technology such that the two stages are integrated on a single silicon chip. Specific objectives are as follows. The nanopositioner controls one translational degree of freedom. The first stage provides a single, discrete displacement of about 50 µm. The second stage moves continuously through a range of 5 µm with 25-nm resolution. Both stages are operated by thermal actuators. The entire nanopositioner is fabricated on a silicon chip by surface micromachining.

The proposed nanopositioner may lead to a number of applications in optics. A silica microsphere might be inserted between two optical fibers to selectively transfer specific wavelengths between them [7]. The sphere would need to be located at some distance from the fibers when no interaction was desired. When a signal was to be transferred, the sphere would need to be moved into position and carefully located in order to minimize the cross-over loss.

Arrays of nanopositioners may be applied to parallel laser printing [8]. Each nanopositioner would scan a laser across a small portion of the print roller. This may reduce the cost of the printer and increase printing speed in comparison with a single laser that scans the entire roller.

A third potential application is the modulation of an optical signal with a pair of gratings [9]. Two gratings with the same period are stacked together. One is shifted relative to the other in the direction perpendicular to the slits. The fraction of the incident power that is diffracted to each order changes with the phase difference of the gratings.
Conformity of the layers in surface micromachining makes it difficult to create detailed structures in two layers at the same location. One solution is to fabricate the gratings in different layers and at separate locations. The first stage of the nanopositioner could move one grating on top of the other. The power delivered to the first diffracted order of the laser could be modulated by changing the relative position of the gratings with the second stage. This application is explored in greater detail in Section 6.4.

The nanopositioner is developed with general capabilities to prove the concept and basic functionality. The proposed applications in optics justify the development of on-chip nanopositioning technology, but the device is not dedicated to any specific application. The object positioned by this device has a nominal size limit of about 200 µm square.

The proposed nanopositioner does not have sensing capability integrated on the silicon chip. MEMS position sensors have recently been developed [10] and may be used in the future; the technology is not sufficiently developed to be utilized at present. Without a sensor it is not possible to implement a control system, so feedback control is excluded from the scope of this project. Position measurements are made from images taken with a scanning electron microscope (SEM) and serve to calibrate, but not control, the device.

Tests are performed on a small number of prototypes. A full statistical analysis of the repeatability of the manufacturing process is beyond the scope of the project, but it has been reported in other works [11–14]. Only a few design variations are produced because space on the MEMS chip is limited.

The novelty of the proposed nanopositioner is that both the coarse- and fine-motion stages are integrated on a single silicon chip. Microactuators have been employed for the second stages of some dual-stage nanopositioners [15–24], but in each of these
cases the first stage is a macro-scale device. The dual-stage nanopositioner has the potential to exceed the ranges of single-stage nanopositioners. It could possibly produce greater forces than other micro-scale nanopositioners because it is driven by thermal actuators.

1.4 Thesis Outline

The first chapter of the thesis introduces fundamental concepts and definitions as necessary to explain the objective of this research. Chapter 2 reviews micropositioners and nanopositioners that have been developed by other researchers and commercial enterprises. It includes descriptions of compliant mechanisms, a microactuator, and the surface micromachining process by which the nanopositioner is fabricated. Chapter 3 discusses the design of the nanopositioner in detail. The design decisions are justified, and the purpose of each component is explained. The analyses of the components comprise Chapter 4. The objectives of each analysis are identified, the methods explained, and the results presented. Chapter 5 defines the components of accuracy and identifies the sources of position error. Tests for determining the accuracy of the nanopositioner are presented. The technique for measuring position is discussed; the uncertainty of the measurement process is quantified through a series of tests. The results of experiments to measure the performance of the nanopositioner are given in Chapter 6. Chapter 7 summarizes the unique contributions that this device makes to the field of mechanical engineering design.
CHAPTER 2  BACKGROUND

This research project builds on the efforts and successes of engineers from many parts of the world. The majority of this chapter is devoted to describing and comparing the many micro- and nanopositioners that have been developed in recent years, both in laboratories and as commercial products. They form the basis for improvements. There follows an explanation of compliant mechanisms and a tool for designing and analyzing them. The thermal actuators that control the dual-stage nanopositioner are described. The last section of this chapter explains the surface micromachining process by which the nanopositioner was fabricated.

2.1 Micropositioners and Nanopositioners

Micropositioners and nanopositioners control the position of an object with accuracy on the order of micrometers and nanometers, respectively. The terms “micro” and “nano” are associated with the resolutions rather than the sizes of the devices. Micro- and nanopositioners may range from several micrometers in size (MEMS) [25] to several meters (e.g. coordinate measurement machines). Positioners generally consist of three sub-systems:
(1) a mechanism that is driven by (2) actuators and (3) tracked by sensors. The following concentrates on the mechanical aspects of nanopositioners, namely the mechanisms and actuators that govern the limits of the best possible performance. The electrical sub-systems (i.e. sensors) monitor and report on performance. The purpose of this review is to provide an understanding of the limits on the state of the art. As such, these limits are best embodied by coverage of the mechanical aspects of positioners. Extensive coverage of precision sensors is provided by Slocum [26].

A wide variety of applications have been proposed for micro- and nanopositioners, and some have been implemented as commercial products. Increases in data storage density have required hard-disk-drive read/write head controllers to move with greater accuracy. Integrated circuit manufacturing requires careful alignment of silicon wafers and masks. Optical communication devices utilize controlled movements on the micrometer scale. Micro- and nanopositioners have the potential to meet these needs. It is anticipated that the performance of positioning systems will improve, as well as the manufacturing processes, and that they will become increasingly common in industry.

Progress in the fields of micro- and nanopositioning will be accomplished through the combined efforts of researchers and commercial ventures. In both research and industry there is a need to evaluate the performance of new devices relative to existing ones; therefore, standard criteria must be established. The following set of measurable characteristics is proposed: degrees of freedom, range, resolution, range-to-resolution ratio, footprint, force, natural frequency, and bandwidth. These are frequently reported in the literature, and they collectively represent both the capability of a device and its suitability for inclusion in larger systems.
The characteristics of a few micro- and nanpositioners from the literature and a sampling of commercially available nanpositioners are reviewed here [27]. The devices are classified according to the principal method of actuation. Five major actuator types are included. Values of the key characteristics are tabulated along with information about sensors and control systems. There are many other characteristics of positioners, such as hysteresis, repeatability, accuracy, and thermal stability, which are not included in the tables because the information is rarely available in the literature. The advantages of each actuator type are discussed. The summary is intended to help researchers and engineers build on the accomplishments of others. The condensed results save time for researchers by directing them to the articles that pertain to their work.

2.1.1 Applications

Numerous applications have been proposed for micro- and nanpositioners, including data storage, manufacturing, high-resolution microscopy, communication, electrical switching, and fluid handling. Second-stage read/write head controllers have been developed for hard disk drives to improve track following accuracy and permit increased track density [15–24]. An atomic force microscope tip may also be manipulated to record and read information [28].

Nanpositioners could perform a variety of precision machining operations [29,30]. They might be configured to assemble micrometer-sized parts [31–36]. Accurate positioners are needed to align silicon wafers for lithography [37–43]. Devices have also been proposed for laser welding [44] and to dress grinding wheels [45,46]. Multi-axis stages may position samples for electron microscopy [47–49], atomic force microscopy
[30,50,51], scanning tunneling microscopy [30,50,52–54], and scanning probe microscopy [51,55–58].

Optical communications devices include switches [59–61], fiber aligners [43,53,62–64], moving mirrors and gratings [56,65], a Fourier transform spectrometer [66], a bar code scanner [67], a variable optical attenuator [68], a phase shifting diffraction interferometer [69], and micro Fresnel lenses [70,71]. Several actuators have been proposed to operate electrical switches or relays [72–76]. Fluid pumps and valves may be useful for biological studies or drug dose regulation [77–80].

2.1.2 Actuator Types

The performance of a positioner is directly linked to the choice of actuator. Therefore, this review begins with a description of the basic physics and a few characteristics of each actuator type. More detailed explanations of the mechanics of microactuators are provided by Madou [81] and Maluf [4].

2.1.2.1 Electrostatic actuators

Electrostatic actuators are capacitors with either air or vacuum as the dielectric. A potential difference between two plates induces an attractive force which is a nonlinear function of the plate separation distance. Factors such as the projected area between the plates and the geometry of the field fringe lines affect the force–displacement relationship. Actuators that move in the direction normal to the plate surfaces generate large forces but have limited range. The interdigitated fingers of a comb drive move in the direction parallel to their length; therefore the separation remains constant and the force is almost independent of displacement (Figure 2.1) [16]. Electrostatic actuators only generate an attractive force.
Positioning devices are usually designed with two actuators oriented in opposite directions to permit both forward and reverse motion. The suspension that guides the actuator can also supply the restoring force [82]. Tables 2.1 and 2.8 present the characteristics of a sampling of electrostatic positioning devices. Typical applied voltages are between 20 V and 60 V [23,82].

2.1.2.2 Piezoelectric actuators

A piezoelectric material is an ionic crystalline solid with asymmetric unit cells. Stress applied to the material distorts the unit cells. The angles between the positive and negative ions change, altering the vector sum of the electric dipoles. This induces an electric field in the crystal in the same direction as the applied stress [4]. The polarity of the field depends on the sign of the stress (tensile or compressive). The principle also works in
reverse: an applied voltage causes strain in the material, and the direction of the strain is controlled by the sign of the voltage. In general, one only needs to apply a voltage to piezoelectric actuators to induce the electric field to actuate them. The current through the actuators, called the leakage current, is negligible because piezoelectric materials have high resistivities. Quartz (SiO₂) and zinc oxide (ZnO) are common piezoelectric materials. Most piezoelectric actuators in nanopositioning systems are made of lead zirconate titanate (PZT), a solid solution of lead zirconate (PbZrO₃) and lead titanate (PbTiO₃). They are

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Italicized values are not explicitly stated in the sources but have been estimated from the available information.

* Information is not available in the source.
usually operated in compression because the compressive strength of PZT exceeds the tensile strength. As these actuators are strain and voltage dependent, one can expect to obtain relatively small displacements for moderate to high voltage inputs. For instance, a displacement of 11.6 µm was obtained with a 20-mm-long stack of thin PZT crystals and a voltage of 100 V [37]. Figure 2.2 illustrates the layout of a piezoelectric nanopositioner. The actuators may come in various geometries; for instance: cylindrical, bi-morph beams, and segmented plates. Tables 2.2, 2.3, 2.9, and 2.10 list the characteristics of piezoelectric positioning devices.

2.1.2.3 Magnetic actuators

Most magnetic actuators exert a force on a permanent magnet by inducing an electric current (about 500 mA) in a conductor coil [33]. The direction of the current determines the direction of the force. Figure 2.3 is a schematic drawing of a magnetic nanopositioner. Other types of magnetic actuators use components such as linear motors. Tables 2.4 and 2.11 contain the characteristics of magnetic positioners.
2.1.2.4 Thermal actuators

Thermal actuators move as electric current flows through thin beams, causing the material to strain and produce useful displacement outputs. As these strains are small, it is generally necessary to mechanically amplify the output. Stress in the beams is predominantly compressive, and buckling is often a cause of failure. Thermal actuators only move in one direction from their isothermal position. Displacement from this position relies on strain; therefore, maximizing the magnitude of this displacement generally requires high temperatures. A common configuration is illustrated in Figure 2.4. Typical inputs are 13 V and 36 mA [72], and the operating temperature is usually about 600 °C [59,76]. The characteristics of thermal positioning devices are listed in Tables 2.5 and 2.12. Care must be taken
when using thermal actuators in precision positioners due to the transient thermal gradients that they may impart to other parts of the machine.

2.1.2.5 Electrochemical actuators

Electrochemical actuators operate by electrolysis of an aqueous solution [80]. The oxidation and reduction reactions convert water to hydrogen and oxygen gases and vice versa. The gas pressure deflects a membrane and does mechanical work. After the electric current stops, the reverse reaction proceeds slowly until the membrane returns to its undeflected position; the anode and cathode may be short-circuited to increase the rate of the reverse reaction. Electrochemical actuators only move in one direction from the isobaric

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Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
state. Figure 2.5 shows a possible layout for the electrodes and membrane. An electrochemical positioning device operates on about 1.6 V and 50 µA [79]. The characteristics of electrochemical devices are listed in Tables 2.6 and 2.13.

2.1.2.6 “Inchworm” actuators

Some of the piezoelectric, thermal, and electrostatic positioning devices operate on the “inchworm principle.” An inchworm moves by gripping a surface with its hind legs while it extends its body and then gripping with its fore legs while retracting its body. Tables 2.7 and 2.14 contain the characteristics of the “inchworm” devices. The piezoelectric drivers grip a track with piezoelectric or electrostatic actuators and use piezoelectric stacks to move forward [28,29,45,46,53,91]. In one device, a piezoelectric hammer strikes an object at a high frequency to cause it to slip in a controlled manner; a pneumatic cylinder advances the hammer [35]. Thermal actuators have been used as legs for a walking robot [94].

The scratch drive actuator is an example of an electrostatic device that uses the “inchworm principle” [70,89,90]. An angled silicon plate is manufactured on a silicon
wafer (Figure 2.6). Opposite electrostatic charges are applied to the plate and substrate, and the resulting force bends the plate toward the substrate. Friction is greater at the rear of the plate, so the front edge slips forward. The rear edge advances when the electrostatic charge is removed. A scratch drive actuator can only be driven in one direction, but opposing scratch drives have been joined with a nonconducting bridge to allow two-way operation [70]. The bridge must be an insulator so that the opposing drives can be controlled independently.

An ultrasonic actuator functions much like a scratch drive. A piezoelectric crystal driven with a sinusoidal voltage source excites bending vibrations in a metal plate supported by four posts [92,93]. The flexure of the plate and an imbalance of friction forces on the posts cause it to move.

The “inchworm” devices are considered as a separate group, rather than classifying them with their respective actuator types, because the actuators are implemented differently. Not being permanently attached to a surface, these devices move far beyond the extension of the actuator alone. The primary characteristic of “inchworm” devices is fric-
tion between the moving parts. Whereas friction introduces hysteresis in traditional machines, these devices harness it to make controlled movements on the nanometer scale. One disadvantage of these actuators is the non-repeatability of friction and the dependence of friction on surface quality (e.g. contamination and surface finish). This generally limits them to resolution on the order of tens to hundreds of nanometers.

There are advantages for each of the actuator types. Electrostatic and thermal devices may be fabricated by surface micromachining, making them small and lightweight. Piezoelectric actuators provide large forces because the ceramic crystals are both stiff and strong in compression. Electrostatic and piezoelectric actuators consume little power while holding a position. Magnetic devices can be made to levitate such that the

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object being positioned is physically isolated from the base. Electrochemical actuators require less voltage than electrostatic and piezoelectric actuators. They are also able to maintain a position for a short time without continuously consuming power.

2.1.3 Performance characteristics

The characteristics of positioning devices differ by orders of magnitude, even among those with the same type of actuator, but a few generalizations are justifiable. This section discusses each of the eight performance characteristics by actuator type. Comparisons across actuator types are not clear because there is significant overlap in the data. Trends between pairs of characteristics (such as range and footprint) are blurred by the uniqueness of the individual devices.

### TABLE 2.4 Magnetic Positioning Devices, Part I

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</tr>
<tr>
<td>Chen et al., 2002 [52]</td>
<td>3</td>
<td>100</td>
<td>50</td>
<td>2.0×10³</td>
<td>49×10³</td>
</tr>
<tr>
<td>Guckel et al., 1998 [73]</td>
<td>1</td>
<td>500</td>
<td>100</td>
<td>5×10³</td>
<td>31</td>
</tr>
<tr>
<td>Jung and Baek, 2002 [33]</td>
<td>6</td>
<td>4×10³</td>
<td>1×10³</td>
<td>4×10³</td>
<td>44×10³</td>
</tr>
<tr>
<td>Mohamed et al., 1994 [41]</td>
<td>2</td>
<td>350</td>
<td>50×10³</td>
<td>7</td>
<td>800</td>
</tr>
<tr>
<td>Rothuizen et al., 2002 [57]</td>
<td>3</td>
<td>100</td>
<td>*</td>
<td>—</td>
<td>230</td>
</tr>
<tr>
<td>de Bhailis et al., 2000 [77]</td>
<td>1</td>
<td>14</td>
<td>*</td>
<td>—</td>
<td>350</td>
</tr>
<tr>
<td>Shen et al., 2002 [61]</td>
<td>1</td>
<td>12</td>
<td>*</td>
<td>—</td>
<td>40×10⁻³</td>
</tr>
<tr>
<td>Li et al., 2001 [68]</td>
<td>1</td>
<td>9</td>
<td>*</td>
<td>—</td>
<td>56</td>
</tr>
</tbody>
</table>

**Italicized values are not explicitly stated in the sources but have been estimated from the available information.**

* Information is not available in the source.
2.1.3.1 Degrees of freedom

The number of degrees of freedom generally depends upon the mechanism sub-component of the positioner. It should be noted that there are a few exceptions in electromagnetically actuated (or levitated) stages. Micro- and nanopositioners frequently have one translational degree of freedom. In some designs, multiple actuators are kinematically linked to control more degrees of freedom, including translations and rotations. For devices with more than one degree of freedom, the tabulated data represent only the translational degree of freedom with the greatest range-to-resolution ratio.

Electrostatic, thermal, electrochemical, and “inchworm” devices usually need only one degree of freedom for their intended application. Piezoelectric and magnetic devices

<table>
<thead>
<tr>
<th>Reference</th>
<th>Degrees of Freedom</th>
<th>Range (µm)</th>
<th>Resolution (nm)</th>
<th>Range-to-Resolution Ratio</th>
<th>Footprint (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubbard and Howell, 2004 [85]</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>143</td>
<td>190×10⁻³</td>
</tr>
<tr>
<td>Oliver et al., 2003 [86]</td>
<td>1</td>
<td>12</td>
<td>*</td>
<td>—</td>
<td>5×10⁻³</td>
</tr>
<tr>
<td>Syms, 2002 [67]</td>
<td>1</td>
<td>550</td>
<td>*</td>
<td>—</td>
<td>3.2</td>
</tr>
<tr>
<td>Guckel et al., 1992 [74]</td>
<td>1</td>
<td>130</td>
<td>*</td>
<td>—</td>
<td>33×10⁻³</td>
</tr>
<tr>
<td>Park et al., 2001 [87]</td>
<td>2</td>
<td>33.4</td>
<td>*</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>Jang et al., 2002 [60]</td>
<td>1</td>
<td>30</td>
<td>*</td>
<td>—</td>
<td>490×10⁻³</td>
</tr>
<tr>
<td>Comtois et al., 1997–1 [84]</td>
<td>1</td>
<td>19.1</td>
<td>*</td>
<td>—</td>
<td>2.8×10⁻³</td>
</tr>
<tr>
<td>Comtois et al., 1997–2 [84]</td>
<td>1</td>
<td>*</td>
<td>*</td>
<td>—</td>
<td>5.5×10⁻³</td>
</tr>
<tr>
<td>Chu and Gianchandani, 2003 [59]</td>
<td>2</td>
<td>19</td>
<td>*</td>
<td>—</td>
<td>36</td>
</tr>
<tr>
<td>Jonsmann et al., 1999 [32]</td>
<td>1</td>
<td>17</td>
<td>*</td>
<td>—</td>
<td>100×10⁻³</td>
</tr>
<tr>
<td>Reid et al., 1996 [65]</td>
<td>1</td>
<td>16</td>
<td>*</td>
<td>—</td>
<td>5.0×10⁻³</td>
</tr>
<tr>
<td>Cragun and Howell, 1999 [72]</td>
<td>1</td>
<td>12</td>
<td>*</td>
<td>—</td>
<td>165×10⁻³</td>
</tr>
<tr>
<td>Lott et al., 2002 [76]</td>
<td>1</td>
<td>11.7</td>
<td>*</td>
<td>—</td>
<td>180×10⁻³</td>
</tr>
<tr>
<td>Que et al., 2001 [88]</td>
<td>1</td>
<td>5</td>
<td>*</td>
<td>—</td>
<td>65×10⁻³</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
often have three or more degrees of freedom. Among the three-degree-of-freedom positioners, some move in three orthogonal directions \((x, y, z)\) \([30, 43, 48, 51, 54, 57, 64, 70]\), while others control position and orientation in a plane \((x, y, \theta_z)\) \([35, 37–40, 52, 92]\). A few piezoelectric and magnetic devices control all six degrees of freedom \((x, y, z, \theta_x, \theta_y, \text{and } \theta_z)\) \([31, 33, 43, 62]\).

2.1.3.2 Range

The range of an electrostatic device is typically between 0.5 µm and 100 µm. Most of the piezoelectric devices have ranges between 5 µm and 200 µm. Similarly, the ranges of most magnetic devices fall between 10 µm and 500 µm. The ranges of thermal devices cluster around 15 µm; in contrast, the ranges of the electrochemical devices span the micrometer scale, from 2 µm to 2 mm. The “inchworm” devices travel in discrete steps with theoretically infinite range. The range is only limited by the size of the surface or track that they crawl on.

Dual-stage positioning devices often have large range-to-resolution ratios. Several piezoelectric devices have been reported that employ electric motors to operate a coarse-motion stage with a range of 200 mm \([39, 40, 42]\). Eight of the electrostatic nanopositioners

<table>
<thead>
<tr>
<th>Reference</th>
<th>Degrees of Freedom</th>
<th>Range (µm)</th>
<th>Resolution (nm)</th>
<th>Range-to-Resolution Ratio</th>
<th>Footprint (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanczyk et al., 2000 [80]</td>
<td>1</td>
<td>2×10³</td>
<td>*</td>
<td>—</td>
<td>280</td>
</tr>
<tr>
<td>Neagu et al., 1997 [79]</td>
<td>1</td>
<td>13</td>
<td>*</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Neagu et al., 1996 [78]</td>
<td>1</td>
<td>2</td>
<td>*</td>
<td>—</td>
<td>1.4</td>
</tr>
</tbody>
</table>

* Information is not available in the source.
and two of the piezoelectric nanopositioners are intended to operate as a second stage on the armature of a hard disk drive [15–24]. A voice coil motor would move the armature through a range of about 22 mm to the desired data track, and the microactuator would improve the alignment of the read/write head with the track. However, the dual-stage head controller has not been demonstrated in the literature. For those devices with two stages, both are included in the tables; the coarse-motion stage is listed first and the fine-motion stage second.

**TABLE 2.7** “Inchworm” Positioning Devices, Part I

<table>
<thead>
<tr>
<th>Reference</th>
<th>Degrees of Freedom</th>
<th>Range (µm)</th>
<th>Resolution (nm)</th>
<th>Range-to-Resolution Ratio</th>
<th>Footprint (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrostatic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akiyama and Shono, 1993 [89]</td>
<td>1</td>
<td>*</td>
<td>10</td>
<td>—</td>
<td>$6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fan et al., 1997 [70]</td>
<td>3</td>
<td>250</td>
<td>27</td>
<td>$9.3 \times 10^3$</td>
<td>2.6</td>
</tr>
<tr>
<td>Fukuta et al., 1999 [90]</td>
<td>1</td>
<td>*</td>
<td>40</td>
<td>—</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Piezoelectric</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang and Zhu, 1997 [46]</td>
<td>1</td>
<td>*</td>
<td>5</td>
<td>—</td>
<td>$10.8 \times 10^3$</td>
</tr>
<tr>
<td>Ni and Zhu, 2000 [45]</td>
<td>1</td>
<td>*</td>
<td>5</td>
<td>—</td>
<td>$35 \times 10^3$</td>
</tr>
<tr>
<td>Liu and Higuchi, 2001 [35]</td>
<td>3</td>
<td>$2 \times 10^3$</td>
<td>10</td>
<td>$200 \times 10^3$</td>
<td>$120 \times 10^3$</td>
</tr>
<tr>
<td>Gao et al., 2000 [29]</td>
<td>1</td>
<td>*</td>
<td>10</td>
<td>—</td>
<td>$3.5 \times 10^3$</td>
</tr>
<tr>
<td>Judy et al., 1990 [53]</td>
<td>1</td>
<td>$50.8 \times 10^3$</td>
<td>70</td>
<td>$730 \times 10^3$</td>
<td>650</td>
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<tr>
<td>Cusin et al., 2000 [28]</td>
<td>1</td>
<td>$9.7 \times 10^3$</td>
<td>300</td>
<td>$32 \times 10^3$</td>
<td>300</td>
</tr>
<tr>
<td>Park et al., 2001 [91]</td>
<td>1</td>
<td>$1 \times 10^3$</td>
<td>$11 \times 10^3$</td>
<td>91</td>
<td>$2.6 \times 10^3$</td>
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<td><strong>Ultrasonic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferreira and Fontaine, 2001 [92]</td>
<td>3</td>
<td>*</td>
<td>10</td>
<td>—</td>
<td>$3.1 \times 10^3$</td>
</tr>
<tr>
<td>Ferreira and Minotti, 1997 [93]</td>
<td>2</td>
<td>*</td>
<td>50</td>
<td>—</td>
<td>$2.4 \times 10^3$</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kladitis et al., 1997 [94]</td>
<td>2</td>
<td>*</td>
<td>$3.75 \times 10^3$</td>
<td>—</td>
<td>100</td>
</tr>
<tr>
<td>Kwon and Lee, 2002 [34]</td>
<td>1</td>
<td>50</td>
<td>$5 \times 10^3$</td>
<td>10</td>
<td>$13 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information. * Information is not available in the source.
2.1.3.3 Resolution

Electrostatic positioning devices have resolutions as small as 1.5 nm and as large as 1 µm. The tabulated resolutions of piezoelectric devices vary from 0.3 nm to 100 nm. There is a wider spread among the magnetic devices, from 4 nm to 50 µm. The “inchworm” devices have resolutions between 5 nm and 11 µm; the step size is adjustable for many of them [28,35,45,46,53,89,90,94]. A few authors state the accuracy of their device instead of the

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoen et al., 2003 [56]</td>
<td>200×10⁻⁶</td>
<td>3.7×10³</td>
<td>*</td>
<td>LDV†</td>
<td>No</td>
</tr>
<tr>
<td>Horsley et al., 1999–1 [19]</td>
<td>12×10⁻⁶</td>
<td>500</td>
<td>1.2×10³</td>
<td>Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Horsley et al., 1999–2 [19]</td>
<td>41×10⁻⁶</td>
<td>500</td>
<td>2.5×10³</td>
<td>LDV†</td>
<td>Yes</td>
</tr>
<tr>
<td>Cheung et al., 1996 [15]</td>
<td>320×10⁻⁹</td>
<td>3.2×10³</td>
<td>11×10³</td>
<td>Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Imamura et al., 1988 [20]</td>
<td>21×10⁻⁶</td>
<td>34×10³</td>
<td>42×10³</td>
<td>LDV†</td>
<td>No</td>
</tr>
<tr>
<td>Xu et al., 1995–1 [54]</td>
<td>43×10⁻⁶</td>
<td>*</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Xu et al., 1995–2 [54]</td>
<td>1.76×10⁻⁶</td>
<td>*</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Manzardo et al., 1999 [66]</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Jaecklin et al., 1992 [82]</td>
<td>100×10⁻⁹</td>
<td>*</td>
<td>*</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Hirano et al., 1998, 1999 [17,18]</td>
<td>111×10⁻⁶</td>
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<td>6.4×10³</td>
<td>LDV†, PES‡</td>
<td>Yes</td>
</tr>
<tr>
<td>Kim and Chun, 2001 [21]</td>
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<td>18.5×10³</td>
<td>2.2×10³</td>
<td>LDV†, Interferometer</td>
<td>Yes</td>
</tr>
<tr>
<td>Jaecklin et al., 1993 [50]</td>
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<td>4.3×10³</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Kim and Kim, 2002 [71]</td>
<td>11.7×10⁻⁶</td>
<td>360</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
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<tr>
<td>Lee et al., 2000 [83]</td>
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<td>238</td>
<td>*</td>
<td>LDV†</td>
<td>No</td>
</tr>
<tr>
<td>Li et al., 2003 [75]</td>
<td>8×10⁻³</td>
<td>*</td>
<td>170</td>
<td>Optical Microscope</td>
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</tr>
<tr>
<td>Sun et al., 2002 [36]</td>
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<td>748</td>
<td>120</td>
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<td>Yes</td>
</tr>
<tr>
<td>Hirano et al., 1998 [16]</td>
<td>330×10⁻⁶</td>
<td>1.9×10³</td>
<td>4×10³</td>
<td>LDV†</td>
<td>Yes</td>
</tr>
<tr>
<td>McConaghy et al., 1998 [69]</td>
<td>*</td>
<td>*</td>
<td>5</td>
<td>Interferometer, Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Toshiyoshi et al., 2002 [23]</td>
<td>330×10⁻⁶</td>
<td>16×10³</td>
<td>21×10³</td>
<td>LDV†</td>
<td>No</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
† Laser Doppler Vibrometer
‡ Position Error Signal from the Read Head of a Disk Drive
resolution [15,17,19,21,22,39,66,82,85]; these values are included in the resolution column because they are of the same order of magnitude and convey similar information. In five cases the authors report that the resolution is limited by sensor capability [31,35,41,52,58].

The ratio of the range to the resolution is a relative measure of accuracy. This ratio is useful for comparing the quality of positioning devices of different sizes. The range-to-resolution ratios of piezoelectric and electrostatic devices are on the order of $10^3$. Dual-stage, magnetic, and “inchworm” devices achieve higher ratios, up to $10^7$ [39].

### TABLE 2.9 Piezoelectric Positioning Devices in the Literature, Part II

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scire and Teague, 1978 [49]</td>
<td>29</td>
<td>110</td>
<td>*</td>
<td>LVDT, Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Ku et al., 2000 [30]</td>
<td>$1.0 \times 10^3$</td>
<td>$1.4 \times 10^3$</td>
<td>210</td>
<td>Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Liu et al., 2003 [40]</td>
<td>1st stage: *</td>
<td>*</td>
<td>Laser Interferometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd stage: *</td>
<td>*</td>
<td>Strain gages</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Chang et al., 1999 [37,38]</td>
<td>500</td>
<td>627</td>
<td>700</td>
<td>LVDT, Interferometer</td>
<td>Yes</td>
</tr>
<tr>
<td>Liu et al., 2001 [42]</td>
<td>1st stage: *</td>
<td>*</td>
<td>Laser Interferometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd stage: *</td>
<td>*</td>
<td>62</td>
<td>50</td>
<td>Yes</td>
</tr>
<tr>
<td>Gao and Swei, 1999 [31]</td>
<td>*</td>
<td>60</td>
<td>Laser Interferometer</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>2nd stage: *</td>
<td>92</td>
<td>50</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Gao et al., 1999 [55]</td>
<td>1.5</td>
<td>525</td>
<td>Laser Interferometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chang and Du, 1998 [47]</td>
<td>567</td>
<td>80</td>
<td>120</td>
<td>Laser Interferometer,</td>
<td>No</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spectrum Analyzer</td>
<td></td>
</tr>
<tr>
<td>Soeno et al., 1999 [22]</td>
<td>*</td>
<td>$20 \times 10^3$</td>
<td>$22 \times 10^3$</td>
<td>LDV†</td>
<td>Yes</td>
</tr>
<tr>
<td>Yang et al., 1996 [44]</td>
<td>$1.2 \times 10^3$</td>
<td>364</td>
<td>600</td>
<td>Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Wang et al., 2002 [24]</td>
<td>*</td>
<td>12.5 $\times 10^3$</td>
<td>*</td>
<td>*</td>
<td>No</td>
</tr>
</tbody>
</table>

*Italicized values are not explicitly stated in the sources but have been estimated from the available information.

* Information is not available in the source.

† Laser Doppler Vibrometer

‡ Linear Variable Differential Transformer
The commercial nanopositioners are mostly driven by piezoelectric stacks because of their excellent stiffness [43,48,51,64]. They achieve smaller resolutions than the research prototypes and have higher range-to-resolution ratios (on the order of $10^5$). The quality of the piezoelectric materials, position sensors, electronics, and electrical shielding used in industry may be responsible for the improved resolution.

### 2.1.3.4 Footprint

The footprint of a positioning device is the area of a circumscribed rectangle; it is a standard comparator of size. Some positioning devices have embedded capacitive sensors.

<table>
<thead>
<tr>
<th>Table 2.10 Piezoelectric Positioning Devices in Industry, Part II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Company and Model Number</strong></td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>nPoint [64] N-XY40Z25A</td>
</tr>
<tr>
<td>nPoint [64] N-XY200Z25A</td>
</tr>
<tr>
<td>Queensgate Instruments [51]</td>
</tr>
<tr>
<td>Mad City Labs [48] Nano-UHV100</td>
</tr>
<tr>
<td>Mad City Labs [48] Nano-LP-200</td>
</tr>
<tr>
<td>Mad City Labs [48] Nano-XYZ</td>
</tr>
<tr>
<td>Mad City Labs [48] Nano-Align</td>
</tr>
<tr>
<td>Physik Instrumente [43] P-611.3S NanoCube</td>
</tr>
<tr>
<td>Physik Instrumente [43] P-587.6CD</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.

* Information is not available in the source.
Others use separate measurement systems, such as a laser Doppler vibrometer (LDV) or a scanning electron microscope. The footprints listed in the tables do not include the space occupied by separate sensors, power supplies, or computer hardware.

Typical piezoelectric actuators are 20 mm long [37], while electrostatic actuators are from 0.3 mm to 2 mm long [19,20]. The two-order-of-magnitude difference in actuator length translates to a four-order-of-magnitude difference in the footprints of some of the devices (10^4 mm^2 versus 1 mm^2). The magnetic and electrochemical devices are usually larger than the electrostatic ones, but smaller than the piezoelectric devices. Thermally actuated devices have the smallest footprints; they are typically less than 1 mm^2. The footprints of the “inchworm” devices are consistent with the type of actuator involved. Scratch

---

**TABLE 2.11** Magnetic Positioning Devices, Part II

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith et al., 1994–1 [58]</td>
<td>64×10^{-3}</td>
<td>*</td>
<td>*</td>
<td>Stylus, Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Smith et al., 1994–2 [58]</td>
<td>108×10^{-3}</td>
<td>*</td>
<td>*</td>
<td>Stylus, X-ray Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Culpepper and Anderson, 2004 [62]</td>
<td>*</td>
<td>110</td>
<td>*</td>
<td>Capacitive</td>
<td>No</td>
</tr>
<tr>
<td>Culpepper and Chen, 2004 [63]</td>
<td>*</td>
<td>93</td>
<td>*</td>
<td>Capacitive</td>
<td>No</td>
</tr>
<tr>
<td>Chen et al., 2002 [52]</td>
<td>32</td>
<td>125</td>
<td>85</td>
<td>Capacitive, Interferometer</td>
<td>Yes</td>
</tr>
<tr>
<td>Guckel et al., 1998 [73]</td>
<td>250×10^{-3}</td>
<td>300</td>
<td>*</td>
<td>Electromagnetic</td>
<td>Yes</td>
</tr>
<tr>
<td>Jung and Baek, 2002 [33]</td>
<td>2.16</td>
<td>3.4</td>
<td>10</td>
<td>*</td>
<td>Yes</td>
</tr>
<tr>
<td>Mohamed et al., 1994 [41]</td>
<td>210×10^{-3}</td>
<td>32</td>
<td>*</td>
<td>Optical Lateral Effect Sensor</td>
<td>Yes</td>
</tr>
<tr>
<td>Rothuizen et al., 2002 [57]</td>
<td>4.5×10^{-3}</td>
<td>90</td>
<td>120</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>de Bhailis et al., 2000 [77]</td>
<td>6×10^{-3}</td>
<td>*</td>
<td>*</td>
<td>Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Shen et al., 2002 [61]</td>
<td>68×10^{-3}</td>
<td>*</td>
<td>2×10^3</td>
<td>*</td>
<td>No</td>
</tr>
<tr>
<td>Li et al., 2001 [68]</td>
<td>65×10^{-6}</td>
<td>*</td>
<td>*</td>
<td>Optical Attenuator</td>
<td>No</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.

* Information is not available in the source.
drives can be as small as $10^{-2}$ mm$^2$, whereas piezoelectric drivers cover areas on the order of $10^4$ mm$^2$.

Piezoelectric and magnetic actuators are well suited to macroscopic nanopositioners that need to move similarly sized objects. Electrostatic and thermal devices are designed for microscopic applications. For example, a second-stage position controller for the read/write head of a hard disk drive is intended to fit on the $800 \mu m \times 600 \mu m$ slider on the armature of the magnetic first-stage actuator [20].

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubbard and Howell, 2004 [85]</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Oliver et al., 2003 [86]</td>
<td>$5.4 \times 10^{-6}$</td>
<td>*</td>
<td>500</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Syms, 2002 [67]</td>
<td>*</td>
<td>100</td>
<td>6.0</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Guckel et al., 1992 [74]</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Park et al., 2001 [87]</td>
<td>*</td>
<td>*</td>
<td>700</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Jang et al., 2002 [60]</td>
<td>*</td>
<td>*</td>
<td>200</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Comtois et al., 1997–1 [84]</td>
<td>*</td>
<td>*</td>
<td>800</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Comtois et al., 1997–2 [84]</td>
<td>$18.8 \times 10^{-6}$</td>
<td>*</td>
<td>*</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Chu and Gianchandani, 2003 [59]</td>
<td>$72.5 \times 10^{-3}$</td>
<td>*</td>
<td>*</td>
<td>Capacitive</td>
<td>No</td>
</tr>
<tr>
<td>Jonsmann et al., 1999 [32]</td>
<td>$15.0 \times 10^{-3}$</td>
<td>*</td>
<td>88</td>
<td>Optical Microscope, Fiber Optic Proximity Sensor</td>
<td>No</td>
</tr>
<tr>
<td>Reid et al., 1996 [65]</td>
<td>$4.4 \times 10^{-6}$</td>
<td>*</td>
<td>*</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Cragun and Howell, 1999 [72]</td>
<td>$31 \times 10^{-6}$</td>
<td>*</td>
<td>500</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Lott et al., 2002 [76]</td>
<td>*</td>
<td>*</td>
<td>$9 \times 10^3$</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Que et al., 2001 [88]</td>
<td>$8.3 \times 10^{-3}$</td>
<td>*</td>
<td>700</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
</tbody>
</table>

*Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
2.1.3.5 Force

Tables 2.8–2.14 list published force values for the same micro- and nanopositioners that were included in Tables 2.1–2.7. The force given in the literature for a particular device refers to either the force output of the actuator, the force required to deflect the suspension to the extent of its range, or the force that the combined actuator and suspension exert on an object. The tabulated values vary widely but are suitable for order-of-magnitude comparisons.

Electrostatic actuators provide forces on the order of 10 µN [20]; piezoelectric actuators generate about 100 N, which is $10^7$ times greater [37]. The forces applied by magnetic and electrochemical actuators are about 100 mN [58,80]. Thermal actuators tend to fit into two classes: meso-scale devices that exert forces on the order of 10 mN, and micro-scale devices that are limited to forces of approximately 10 µN. The forces provided by the “inchworm” devices are typical of their actuator types, although size differences lead to some exceptions.

Electrostatic and magnetic actuators are fundamentally different from piezoelectric and thermal actuators because they do not have a physical connection between the refer-

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanczyk et al., 2000 [80]</td>
<td>$142 \times 10^{-5}$</td>
<td>*</td>
<td>*</td>
<td>Micrometer Caliper</td>
<td>No</td>
</tr>
<tr>
<td>Neagu et al., 1997 [79]</td>
<td>$200 \times 10^{-3}$</td>
<td>*</td>
<td>$2 \times 10^{-3}$</td>
<td>Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Neagu et al., 1996 [78]</td>
<td>$5 \times 10^{-3}$</td>
<td>*</td>
<td>$14 \times 10^{-3}$</td>
<td>Atomic Force Microscope</td>
<td>No</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
ence frame and the output. The electrostatic and magnetic fields typically produce less force than strain in a solid material, with the exception that magnetic actuators usually generate more force than thermal actuators because they are larger.

The ultrasonic positioning devices deliver a relatively low force of 1 N, in comparison with other piezoelectric devices, because they rely on their own weight to create friction with the surface that they slide on. The piezoelectric drivers, on the other hand, actively grip the track.

### TABLE 2.14 “Inchworm” Positioning Devices, Part II

<table>
<thead>
<tr>
<th>Reference</th>
<th>Force (N)</th>
<th>Natural Frequency (Hz)</th>
<th>Speed (mm s⁻¹)</th>
<th>Sensors</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrostatic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akiyama and Shono, 1993 [89]</td>
<td>*</td>
<td>*</td>
<td>81×10⁻³</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Fan et al., 1997 [70]</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Fukuta et al., 1999 [90]</td>
<td>60×10⁻⁶</td>
<td>*</td>
<td>10×10⁻³</td>
<td>Electron Microscope</td>
<td>No</td>
</tr>
<tr>
<td><strong>Piezoelectric</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang and Zhu, 1997 [46]</td>
<td>200</td>
<td>1.8×10³</td>
<td>6</td>
<td>Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td>Ni and Zhu, 2000 [45]</td>
<td>8.0×10³</td>
<td>*</td>
<td>*</td>
<td>Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Liu and Higuchi, 2001 [35]</td>
<td>50</td>
<td>200</td>
<td>1</td>
<td>LDV†, Capacitive</td>
<td>Yes</td>
</tr>
<tr>
<td>Gao et al., 2000 [29]</td>
<td>*</td>
<td>432</td>
<td>300×10⁻⁶</td>
<td>Laser Interferometer</td>
<td>Yes</td>
</tr>
<tr>
<td>Judy et al., 1990 [53]</td>
<td>148×10⁻²</td>
<td>*</td>
<td>476×10⁻³</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Cusin et al., 2000 [28]</td>
<td>140</td>
<td>*</td>
<td>310×10⁻³</td>
<td>*</td>
<td>No</td>
</tr>
<tr>
<td>Park et al., 2001 [91]</td>
<td>450</td>
<td>1.31×10³</td>
<td>11</td>
<td>Laser Interferometer</td>
<td>No</td>
</tr>
<tr>
<td><strong>Ultrasonic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferreira and Fontaine, 2001 [92]</td>
<td>1</td>
<td>*</td>
<td>300</td>
<td>LDV†</td>
<td>Yes</td>
</tr>
<tr>
<td>Ferreira and Minotti, 1997 [93]</td>
<td>1</td>
<td>*</td>
<td>300</td>
<td>LDV†</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kladitis et al., 1997 [94]</td>
<td>*</td>
<td>*</td>
<td>7.55×10⁻³</td>
<td>Optical Microscope</td>
<td>No</td>
</tr>
<tr>
<td>Kwon and Lee, 2002 [34]</td>
<td>50×10⁻⁶</td>
<td>*</td>
<td>400×10⁻³</td>
<td>*</td>
<td>No</td>
</tr>
</tbody>
</table>

Italicized values are not explicitly stated in the sources but have been estimated from the available information.
* Information is not available in the source.
† Laser Doppler Vibrometer
2.1.3.6 *Natural frequency*

Stiff actuators (and those with very little mass) tend to have high natural frequencies. The natural frequency influences the speed with which an actuator responds to a command [95]. Feedback control systems with faster actuators are able to follow inputs at higher frequencies and accomplish positioning tasks in less time.

The natural frequency columns in the tables include resonant frequencies for some devices because they are the only values stated by the authors. The natural frequency of a device is nearly equal to the resonant frequency when there is little damping, as is typical with nanopositioning systems.

Many electrostatic devices have natural frequencies on the order of a few kilohertz because of their low masses. Piezoelectric devices have natural frequencies of several hundred Hertz because of their high stiffnesses. The natural frequencies of the piezoelectric “inchworm” devices [29,35,46,91] compare well with those of other piezoelectric devices. The masses of magnetic devices are comparable to those of piezoelectric devices but the stiffnesses are lower, so the natural frequencies are on the order of 100 Hz.

Thermal actuators have very little mass, like electrostatic actuators. However, the dynamic response of a thermal actuator is not limited by momentum, but by heat transfer, making it a first-order system. For this reason the natural frequencies of thermally actuated devices are seldom measured or reported. One particular thermal actuator drives a 14-mm-long cantilever beam at its resonant frequency of 100 Hz [67], and a six-axis micro-scale positioner was shown to have a natural frequency of 100 Hz [96]. Electrochemical actuators are first-order systems, as well; therefore, natural frequencies are not reported for them, either.
2.1.3.7 **Bandwidth**

As a dynamic system is driven with a control signal of constant amplitude and increasing frequency, the amplitude of oscillation eventually declines, although for a second-order system it climbs to a resonant peak first. When the response decreases to 71% of the low-frequency amplitude, the error is $-3 \text{ dB}$. The bandwidth of a dynamic system is the highest sinusoidal input frequency that it can follow with error less than $-3 \text{ dB}$ [95].

The bandwidths of electrostatic, piezoelectric, and magnetic positioning devices are on the same order of magnitude as their respective natural frequencies. If the bandwidth of a second-order system is known and not the natural frequency, it is reasonable to assume that the natural frequency is on the same order of magnitude as the bandwidth, and vice versa. For a first-order system, the bandwidth is the reciprocal of the time constant; some of the bandwidths in Tables 2.12 and 2.13 that are not explicitly stated in the literature are estimated from the time constant. The time constants of thermal actuators are usually between 0.1 ms and 10 ms, allowing bandwidths as high as 9 kHz [72,76]; the median value is 500 Hz [86]. Electrochemical actuators have time constants on the order of 100 s and corresponding bandwidths of about $10 \times 10^{-3} \text{ Hz}$ [78].

The “inchworm” devices are characterized by speed rather than bandwidth because it is a more useful metric for temporal behavior. Bandwidth only applies to continuous motion, which for an “inchworm” device means displacement less than a single step. When the device grips and releases the track it is sliding on, continuity of motion is lost. The speed of an “inchworm” device specifies the time required to complete movements thousands of times greater than the step size.
2.1.3.8 Sensors

Sensors are one of the main sub-components of positioning systems. Although they do not generally set the fundamental limit on the performance of a positioner, they monitor the in-situ performance of the device and, therefore, set limits on useful performance. For instance, trueness is almost entirely determined by the sensors because systematic errors can be calibrated out if they are known. As was mentioned previously, the resolution of a positioning system cannot be determined if the sensor resolution is larger (page 28). Similarly, the random error of a positioner can only be measured if the sensor error is negligible in comparison. The accuracy of positioning devices and position measurements is discussed further in Chapter 5.

There are no dual-stage sensors. This is because the second stage would only measure position relative to the first stage; therefore, its uncertainty would be at least as large as that of the first stage, and it would be entirely useless. A sensor for a dual-stage positioning system must both cover the entire range and achieve the required accuracy.

Capacitive gap sensors, laser Doppler vibrometers, and laser interferometers are the most frequently used position sensors. Many researchers take position measurements from images acquired with an optical microscope or a scanning electron microscope. Strain gages are useful for measuring the deflections of macroscopic compliant suspensions.

2.1.3.9 Feedback control

The majority of the piezoelectric devices and some of the electrostatic and magnetic devices include feedback control systems to improve accuracy and response time. Feed-
back control is most frequently implemented with capacitive gap sensors or interferometry systems. Control systems are especially necessary to correct for the inherent hysteresis and drift in piezoelectric actuators [30,35,38].

2.1.4 Summary

A number of micro- and nanopositioners have been developed in recent years. Key characteristics are identified that make it possible to compare the performance of these devices. Values of the characteristics have been obtained from the literature and compiled in convenient tables. Five major types of actuators are included. Each has advantages that may make it preferable for the design of a particular positioning device.

Electrostatic and thermal devices are small and may be mass produced by microfabrication methods. With ranges on the order of micrometers and forces on the order of micronewtons, they are ideal for manipulating microscopic objects. Electrostatic nanopositioners with feedback control systems operate with bandwidths greater than 1 kHz. Thermal actuators may be operated at low voltages (less than 5 V).

Piezoelectric and magnetic devices are better suited to the positioning of macroscopic objects. Although their ranges are usually measured in micrometers, they are large enough to manipulate objects with masses between 5 g and 5 kg. The piezoelectric devices generate larger forces and respond more quickly to commands.

Electrochemical devices operate at low voltages and temperatures and, like electrostatic and piezoelectric actuators, have the ability to maintain a position without continuous power. They are small but provide a moderate force. Dual-stage devices and those that operate on the “inchworm” principle combine large ranges with small resolutions.
The current state of micro- and nanopositioning technology has been summarized. With an understanding of what has been done in the field of precision position control, engineers are able to design machines with improved performance. The proposed nanopositioner uses thermal actuators because they develop large forces with reasonable voltage and current and because they are sufficiently accurate for nanopositioning (Section 3.1).

2.2 Compliant Mechanisms

“Compliant mechanisms gain at least some of their mobility from the deflection of flexible members” [97]. They are superior to traditional rigid-body mechanisms in many product designs. Compliant mechanisms use fewer parts and require less assembly. A single flexible segment has the same functionality as two rigid links, a pin joint, and a torsional spring. It incorporates energy storage with a degree of freedom. Some products are manufactured as one part (i.e. an egg carton) so they do not need to be assembled. A mechanism is fully compliant if it has no kinematic joints (sliding, revolute, or rolling). Eliminating kinematic joints from a mechanism reduces friction and backlash and, therefore, increases accuracy.

The force on a cantilever beam is computed with a simple formula when the deflection is small. Modelling large deflections accurately requires elliptic integral equations, which are often impractical to solve. The pseudo-rigid-body model (PRBM) is a simpler mathematical tool [97]. It finds the link lengths and torsional spring stiffnesses of a rigid-link mechanism with behavior that closely approximates that of a particular compliant mechanism. The rigid-link mechanism is analyzed with the methods of kinematics. The principle of virtual work relates the forces acting on the mechanism to the distance it
moves. The PRBM is simple enough to allow quick iterations on the design. The error in
the PRBM position approximation is usually less than 0.5% [97].

2.3 Thermomechanical In-plane Microactuator

The Thermomechanical In-plane Microactuator (TIM) consists of thin beams arranged in
a chevron pattern around a shuttle [72]. The outer ends of the beams are connected to
anchors that provide fixed end constraints. Figure 2.7a is a drawing of a TIM. The heat
dissipated by an electric current flowing through the beams causes them to expand, and,
because of the constraints, the beams buckle (Figure 2.7b). The angle of the beams biases
them to buckle in the intended direction. The shuttle moves along a straight path because
of the symmetry of the chevron pattern.

TIMs operate at low current and require less voltage than electrostatic or piezo-
electric actuators. A typical TIM in air draws 30 mA and 6 V. The requirements drop to
14 mA and 3 V in vacuum (as when imaging with a scanning electron microscope) [98].

The TIM is a fully compliant mechanism and thus has no revolute or sliding joints
to cause backlash. All of the motion is enabled by the compliance of the expansion beams.
The beams suspend the shuttle above the substrate so that there is no friction to hinder pre-
cise motion. The simplicity of its monolithic design makes the TIM ideal for surface
micromachining.

An Amplified Thermomechanical In-plane Microactuator (ATIM) has a set of
amplifying beams between two TIMs (Figure 2.8). The TIMs compress the amplifying
beams, and, as they buckle, the shuttle moves. An ATIM has a greater range than a TIM
but provides less force.
2.4 Surface Micromachining

BYU has access to MEMS fabrication technology through the Multi-User MEMS Processes (MUMPs), a service of MEMSCAP [99], and the Sandia Ultra-planar Multi-level
MEMS Technology (SUMMiT) at Sandia National Laboratories [100]. A brief overview of MUMPs follows. Figure 2.9 illustrates the layers that are created in MUMPs.

A 0.6-µm-thick layer of silicon nitride (Si₃N₄) is grown on a phosphorus-doped, single-crystal-silicon wafer by chemical vapor deposition (CVD) [12]. It electrically insulates the MEMS devices from the conductive wafer. A base layer of polycrystalline silicon (or polysilicon) is deposited to a thickness of 0.5 µm. It is covered by a photolithographic mask, which is exposed with a laser and developed so that it has the geometry specified in
a computer drawing. A reactive ion etch (RIE) shapes the silicon according to the mask; then the mask is removed. A sacrificial layer of phosphosilicate glass (PSG) is deposited, masked, and etched like the base polysilicon layer. It separates subsequent polysilicon layers and is all removed at the end of the production process.

A second polysilicon layer is deposited with a thickness of 2.0 µm. A thin layer of PSG is deposited on the silicon. The wafer is annealed at 1050 °C for one hour to reduce residual stresses in the silicon and to dope the silicon with phosphorus from the glass. The glass is lithographically etched, as before, and becomes the mask for the RIE process. The second polysilicon layer is the first structural layer. Machine parts created in it are free to move relative to the substrate, whereas the base layer is not. Holes patterned in the glass allow the silicon layer to fuse to the substrate, creating anchor points.

Another layer each of PSG and polysilicon are patterned in the same manner to create a second structural layer, which is 1.5 µm thick. The second structural layer conforms to the layers below; it dips down where there are gaps in the first structural layer (Figure 2.9b). Holes in the PSG allow the polysilicon to form anchors to the first structural layer or to the substrate. A 0.6-µm-thick layer of gold is deposited and patterned on the top layer of polysilicon to form electrical traces. The wafer is diced into 1-cm-square chips and shipped to the customers. The customers release the mechanisms by immersing each chip in hydrofluoric acid for 170 s to remove the PSG. The chip is placed in hydrogen peroxide (H₂O₂) for 300 s to roughen the surfaces and reduce adhesive forces. The chip is soaked in water to remove the acid and peroxide solutions. The water is removed by rinsing the chip in isopropyl alcohol and baking it at 110 °C for 15 minutes. The MEMS are then ready for testing.
The development of the proposed nanopositioner includes design, analysis to predict the functionality of the design, and testing of a prototype. The first section of this chapter explains the major design decisions and gives reasons for them. The second section explores four methods of delivering power to the second stage. A unique nanopositioner is created to test each method. The third section explains additional features of the nanopositioners, including a design for a rotational nanopositioner.

3.1 Design Decisions

The nanopositioner is produced by surface micromachining to take advantage of reduced size and cost. It is fabricated in MUMPs because batches are scheduled more frequently and the production time is shorter than with SUMMiT. Micro-scale nanopositioners fit in tighter packages, weigh less, and use less electrical power than macro-scale nanopositioners. The nanopositioner would cost less to mass produce by surface micromachining than by conventional processes such as electrical discharge machining (EDM). Size and cost
are two factors that make the device significantly more marketable for possible applications.

Most three-degree-of-freedom positioners are created by stacking together multiple one-degree-of-freedom actuators. Therefore, it is only necessary to demonstrate nanopositioning with one degree of freedom. The nanopositioner controls translation in one direction parallel to the surface of the silicon chip. The complexities of stacking up other degrees of freedom are left to future research.

The nanopositioner is designed with two stages to achieve both a large range and good resolution. The first stage toggles between two discrete positions with a range of approximately 50 µm. The second stage moves continuously over a smaller range to adjust the final position. It has one translational degree of freedom and moves in the same direction as the first stage. A bistable mechanism [101] holds the first stage in either of its two positions in the presence of disturbance forces. The bistable mechanism requires an actuator with a long range and a high output force to transition it between the two stable equilibrium positions, but it maintains its position after the actuator turns off, thus conserving power. The second-stage actuator requires low-level, continuous input to hold its position.

The nanopositioner is powered by thermal actuators (Section 2.3) because they meet the force and displacement requirements and have sufficient accuracy (Table 2.5). Figure 3.1 is a micrograph of one half of the ATIM that was selected to drive the first stage of the nanopositioner. Figure 2.8 is a drawing of the same ATIM. One set of ATIMs pulls the first stage of the nanopositioner from the as-fabricated position to the second position; another set of ATIMs moves it in the reverse direction. Multiple ATIMs are connected in
each set to provide more force. A TIM controls the second stage. The actuators are compatible with surface micromachining and have current and voltage requirements that can be met by standard electrical power supplies. Although thermal actuators are fully compliant, they have sufficient stiffness for 25-nm accuracy; this assertion is supported in Section 6.1.

An existing bistable mechanism design was selected because it was known to move at least 50 µm and exhibit distinct bistable behavior. The bistable mechanism has two beams, one on each side of the shuttle, that buckle as the shuttle is displaced (Figure 3.2). Each buckling beam consists of a stiff segment between two flexible segments. The flexures at the ends of the buckling beams soften the constraints and relieve stress. Figure 3.3 is a micrograph of one buckling beam.
Compliant mechanisms are employed for as many of the components of the nano-positioner as possible because they experience less friction and backlash than rigid-link mechanisms. Pin joints are avoided because they hinder accurate position control and because they are difficult to make with MUMPs. The thermal actuators and the bistable mechanism are fully compliant. Some sliding joints are necessary to provide stiff support for the second-stage actuator.
3.2 Dual-stage Actuation

Independent operation of the first and second stages requires two independent inputs. The coarse-motion stage receives electric current through traces and wires attached to the chip. The input for the fine-motion stage may be electrical or mechanical. Four nanopositioners were designed to explore both of these options for controlling the second stage.

The first two nanopositioners discussed in this chapter, NanoTran 1 and NanoTran 2, demonstrate the possibility of providing an electrical input to the second stage. They have similar design constraints and challenges. The second stage of the third nanopositioner, NanoTran 3, receives a mechanical input from actuators mounted on the substrate. The fourth nanopositioner, NanoTran 4, does not have two stages; it utilizes the bistable mechanism to provide both coarse and fine position control. Table 3.1 presents basic characteristics of the four nanopositioner designs.

3.2.1 NanoTran 1

Figure 3.4 shows the layout of the NanoTran 1. According to the decisions explained in Section 3.1, the first-stage actuators are sets of ATIMs, and the second-stage actuator is a

<table>
<thead>
<tr>
<th>Nanopositioner</th>
<th>Number of ATIMs</th>
<th>Number of Bistable Mechanisms</th>
<th>Method of Fine Motion Control</th>
<th>Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>NanoTran 1</td>
<td>8</td>
<td>4</td>
<td>TIM</td>
<td>$4.3 \text{ mm} \times 3.1 \text{ mm}$</td>
</tr>
<tr>
<td>NanoTran 2</td>
<td>4</td>
<td>2</td>
<td>Compact TIM</td>
<td>$3.5 \text{ mm} \times 1.6 \text{ mm}$</td>
</tr>
<tr>
<td>NanoTran 3</td>
<td>4</td>
<td>1</td>
<td>Mechanical Transmission</td>
<td>$3.4 \text{ mm} \times 1.6 \text{ mm}$</td>
</tr>
<tr>
<td>NanoTran 4</td>
<td>4</td>
<td>2</td>
<td>Thermal Actuation of the Bistable Mechanism</td>
<td>$3.3 \text{ mm} \times 1.6 \text{ mm}$</td>
</tr>
</tbody>
</table>
TIM. The first stage consists of two sections that have different electrical potentials during the fine motion. The TIM that actuates the second stage spans the gap between the sections and forms the only path for current to flow from one section to the other. The sliding couplers attached to the first-stage actuators allow them to retract while the first stage remains stationary.

In order for the second stage to work, the TIM must be tightly constrained in the transverse direction (the horizontal direction in Figure 2.7). When it is actuated, it pushes outward on the sections of the first stage and must be resisted in order to generate a useful displacement in the intended direction. If a mechanical link between the two sections of the first stage were made of polysilicon, it would draw current away from the TIM. It would also heat up and expand, making it ineffective as a displacement constraint. An insulating material, such as hardened photoresist, may be used to couple actuators with

Figure 3.4  Schematic drawing of NanoTran 1
different electrical potentials [70]. However, this would require additional processing after the MEMS chip was fabricated. Instead, anchored guides are placed on either side of the TIM to constrain the thermal expansion (Figure 3.5). The second-stage TIM slides along the plates while the first stage operates. When the TIM expands, it first closes the gaps on either side and contacts the anchored plates; then it moves the second stage forward. Figure 3.6 is a magnified view of the gap on the right side of the TIM shown in Figure 3.5. The TIM closes the gap between the first stage (Figure 3.6a) and the anchored guide (Figure 3.6b).
The two sections of the first stage may be driven by separate sets of ATIMs, as in NanoTran 1 (Figure 3.4), or by the same set of ATIMs, as in NanoTran 2 (Section 3.2.2). Placing two ATIMs side by side gives NanoTran 1 a large footprint: 4.297 mm × 3.082 mm. Figure 3.7 is an image of NanoTran 1 composed of fifteen scanning electron micrographs. The two sections of the first stage are spread far enough apart that each must have its own bistable mechanisms (Figure 3.7b).

Electric current is delivered to the sliding TIM (Figure 3.7d) not only through a pair of electrical contacts (Figure 3.7e) [102] but also through the bistable mechanisms (Figure 3.7b). The beams of the bistable mechanisms are covered with gold to increase their electrical conductivity. Figure 3.8 shows segments of bistable mechanisms with and without the gold layer for comparison. The number of beams in the TIM and, hence, its stiffness are limited by the current-carrying capacity of the electrical contacts and bistable

Figure 3.6  The second-stage TIM of NanoTran 1 closes the gap between (a) the first stage (Figure 3.5a) and (b) the anchored guide (Figure 3.5d)
Figure 3.7  NanoTran 1: (a) ATIMs, (b) bistable mechanisms, (c) sliding couplers, (d) second-stage TIM, and (e) electrical contacts
mechanisms. In practice, the electrical contacts failed to conduct, so the bistable mechanisms set the current limit. If the ATIMs were capable of actuating twice as many bistable mechanisms, the current limit would be doubled, and there could be twice as many beams in the second-stage TIM. The present design requires each ATIM to move one bistable mechanism. The advantage of the NanoTran 1 design is that the two sections of the first stage are electrically isolated; there is only one path for current to flow between them, and that is directly through the second-stage TIM.

**Figure 3.8** Magnified views of (a) a plain beam from the bistable mechanism in NanoTran 4 (Figure 3.3) and (b) a gold-coated beam from the bistable mechanism in the rotational nanopositioner.
The bistable mechanism was chosen because it switches at a low enough force for the ATIM. Consequently, it has low stiffness in the second stable position. If the first stage were allowed to stop at that position it would have poor repeatability. Friction would apply a resisting force that would be different with each actuation, and the first stage would stop at the position where the force applied by the bistable mechanism equaled the friction force. Friction forces acting on the second stage might also cause the first stage to move. Such random behavior would be unacceptable: the second stage needs a consistent starting point for its motion. The bistable mechanism closes the electrical contacts near the position at which it exerts the greatest forward force. If this is greater than the friction force resisting the motion of the second stage, there is no problem with the first stage moving during the fine motion.

3.2.2 NanoTran 2

NanoTran 2 is designed to be more compact than NanoTran 1. Both sections of the first stage are pulled by one set of ATIMs (Figure 3.9). The ATIMs are connected to each sec-
tion of the first stage by a sliding coupler (Figure 3.10). The first stages of all the nanopositioners use sliding couplers of the same design. The sliders allow the ATIMs to pull the first stage through the coarse motion and then turn off while the fine motion occurs. When the bistable mechanism switches and the ATIMs retract, the two parts of the sliding coupler do not necessarily contact each other because there is no force to maintain contact. If they do touch, the electrical contact resistance is expected to be much greater than the resistance of the TIM; therefore, the current will flow mainly through the TIM.

In the NanoTran 2 configuration there is not space for each section of the first stage to have a separate bistable mechanism; the beams of the bistable mechanism must be split apart and the second-stage actuators located between them (Figure 3.9). A bistable mechanism is placed at each end of the first stage for stability. An ordinary TIM would make the second stage about 480 µm wide and 250 µm long. One problem with a sliding stage of these dimensions is the tendency to bind up in the anchored guides. Conventional wisdom dictates that a slider be longer than it is wide to prevent binding. In order to reduce the width of the first stage, a compact TIM is designed (Figure 3.11b). The expansion beams are interlaced so that the TIM is only 280 µm wide, 58% of the width of an
ordinary TIM. The shuttle weaves between the expansion beams to connect them. Figure 3.12 is an image of the entire nanopositioner. With the compact TIM, NanoTran 2 has a footprint of $3.520 \text{ mm} \times 1.632 \text{ mm}$; it is 43% as large as NanoTran 1. Electric current is delivered to the second stage through electrical contacts and gold-coated bistable mechanisms, in the same manner as NanoTran 1. The shuttles of the compact TIMs are also covered with gold to reduce resistance.

The first stage of NanoTran 2 has a tendency to buckle out of the plane in which it is intended to move. The buckling load is strongly sensitive to length, and the beams of the compact TIM that are loaded in compression have the same combined length as a regular
TIM. Furthermore, it is suspended between the long beams of the bistable mechanism. Out-of-plane buckling may make the TIM inoperable.

Another problem with placing the second-stage TIM between the beams of the bistable mechanism is that the actuation of the TIM affects the stability of the bistable mechanism. The TIM pushes outward on the sides of the sliding frame and compresses the beams of the bistable mechanism until it contacts the fixed guide blocks. Although the gap is small, the transverse deflection might cause the first stage to shift, which would hinder the repeatability of the second stage. This problem is ameliorated by placing the electrical contacts such that the bistable mechanism stops prior to the second stable equilibrium position, as with NanoTran 1.
3.2.3 NanoTran 3

The fine-motion stage of NanoTran 3 receives a mechanical input from two TIMs; there is one on either side of the first stage. Figure 3.13 is a schematic drawing, and Figure 3.14 is an image of the actual device. The TIMs are identical to those that operate the ATIMs. The
ATIMs move the first stage into position between the two TIMs so that the shuttles of the TIMs align with contact points on the first stage. Small gaps between the TIMs and the first stage facilitate the coarse motion. The TIMs close the gaps and deflect the first stage. An amplifier mechanism mounted on the first stage converts the displacement of the TIMs to the same direction as the coarse motion and increases its magnitude. The combination of the TIMs and the amplifier mechanism is functionally equivalent to an ATIM. The first stage has flexible members that provide stiff support for the amplifier mechanism in the direction of the coarse motion yet minimal resistance to the action of the TIMs. Figure 3.15 shows the second stage integrated with the first stage. The footprint of NanoTran 3 is 3.431 mm × 1.632 mm.

Figure 3.15 The second stage of NanoTran 3 (rotated 90° counter-clockwise from Figure 3.14): (a) first-stage shuttle, (b) second-stage TIMs, (c) sliding couplers, (d) flexures, (e) amplifier mechanism, (f) second-stage shuttle, and (g) ruler
The bistable mechanism holds the coarse-motion stage against an anchored plate in its second position so that the TIMs grip it in the same place each time they actuate. However, the gaps remain a source of random position error. The rough edges of the mating parts mesh differently each time, and the surfaces change with wear. The random error due to gap closure may be eliminated during operation by maintaining enough current in the TIMs to keep the gaps closed.

The sliding couplers on the TIMs (Figure 3.15c) enable the first stage to move freely until the TIMs are energized. Figure 3.16 shows the sliding coupler between one of the TIMs and the first stage. The shuttles of the TIMs overlap the first stage to hold it down and are themselves prevented from moving out of the fabrication plane by anchored guide blocks located on either side of the TIM shuttles. For a separate discussion of the design and characterization of NanoTran 3, see [103].
3.2.4 NanoTran 4

Figure 3.17 illustrates the layout of the fourth nanopositioner. NanoTran 4 combines the coarse and fine motion by actuating the bistable mechanism. The second stable position is highly sensitive to changes in the length of the buckling beams. A small electric current through the beams causes enough thermal expansion to shift the second stable position by the 5 µm required for the fine motion. One bistable mechanism is placed at each end of the shuttle to stabilize it against rotation. Sliding couplers connect the shuttle to the ATIMs. These components are shown in Figure 3.18. The shuttle of NanoTran 4 does not contact rigid stops like the first stages of the other nanopositioners because there is no part of the shuttle that does not undergo the fine motion as well as the coarse motion. The details of the shuttle and bistable mechanisms are visible in Figure 3.19.

The bistable mechanisms in NanoTran 4 are less stiff than the TIMs that operate the fine-motion stages of the other nanopositioners. This limitation is governed by the stiffness of the ATIMs. If the design of the ATIMs were improved or the number of ATIMs
increased, more bistable mechanisms could be added, and the stiffness of the nanopositioner could be increased.

NanoTran 4 has the advantage of a continuous mechanical connection between the shuttle and the substrate. The sliding TIMs in the other nanopositioners must all close a 440-nm-wide gap between the sliding frame and the guide on either side. Therefore, less hysteresis is expected with the thermally actuated bistable mechanism than with the TIMs. The synthesis of the coarse- and fine-motion stages into one mechanism reduces the footprint of the nanopositioner. NanoTran 4 requires $3.257 \times 1.632$ mm of surface area, slightly less than NanoTran 2 or NanoTran 3.

3.3 Additional Features

The two structural layers provided in MUMPs are combined in the fabrication of the thermal actuators, making the expansion beams 3.5 µm thick. The beams have a finished
width of 3 µm, the minimum beam width that may be reliably produced in MUMPs. The double-layer design increases the force output of the actuators because the beams are more likely to buckle in the intended direction and not out of the plane of motion. As a precaution against out-of-plane buckling, guides are placed on either side of the ATIM shuttles to keep them close to the substrate. The guides overlap the shuttles and are anchored to the substrate. Guides are also placed near the bistable mechanisms.

The TIMs that power the ATIM are connected in a parallel electric circuit. Not only does this mean that if one breaks the other maintains some functionality, but, more importantly, it equalizes the potential at each end of the amplifying chevron so no current
is conducted through it. The amplifying beams of some early prototypes melted before the expansion beams because they drew too much current.

The ATIMs are set to pull the first stages rather than pushing them in order to prevent them from buckling. It is known that the elastic strain energy stored in the ATIM during its heating stage is available to do work during the cooling stroke, making the ATIM more powerful in that direction. The ATIMs could be designed to move the first stage while cooling; however, doing so would require a complex latch system. Instead, the ATIMs connect to the first stage with simple couplers and actuate the stage during the heating stroke.

Two sets of markers are provided to indicate the position of the second stage relative to the substrate. The primary marker is a protrusion from the shuttle of the second stage (Figure 3.20a). A ruler anchored to the substrate near the shuttle has a series of similar protrusions, or fingers, that resemble a comb (Figure 3.20b). The marker and the nearest finger on the ruler may be viewed together in the SEM. A method for measuring the distance between the marker and finger is detailed in Section 5.2.1. The secondary marker is a pair of circular holes in the shuttle (Figure 3.20c). When the first stage is in its second position, the holes line up with an identical pair of holes in a block of polysilicon that is anchored to the substrate (Figure 3.20d). Both pair of holes remain visible in the same SEM image as the second stage moves through its full range. The four holes may be located with image processing software, and the position and orientation of the shuttle may be derived from the hole locations. No attempt is made in this research to utilize the secondary marker.
The SEM bombards the MEMS chip with a beam of high-energy electrons. Many escape from the sample and are detected. Those that are absorbed must have a path to the microscope ground; otherwise, they accumulate and create a charge that deflects the electron beam, yielding poor image quality. A blanket of polysilicon is laid under the measurement tools to collect electrons that would otherwise penetrate the silicon nitride layer, which is not conductive. The blanket is isolated from the actuators so that it does not short-circuit them. Two methods of grounding the polysilicon blanket are implemented. In NanoTran 1 and NanoTran 4, the blanket connects to a bond pad which is linked to the microscope stage (Figure 3.19e). In NanoTran 2, NanoTran 3, and the rotational nanopositioner, the nitride layer is breached in a small area to allow the polysilicon layers to bond with the substrate. The chip must be mounted on a grounded sample holder to complete
the current path. The polysilicon plate that electrically connects the blanket to the chip is attached to the measurement ruler (Figure 3.20e). Both methods resulted in proper grounding of the polysilicon blanket. In some SEM images, the nitride appears bright because of charge accumulation, but the polysilicon appears dark (Figures 3.3, 3.5, and 3.15).

A rotational nanopositioner is designed with the same layout as NanoTran 2 (Figure 3.9) except that one of the compact TIMs is reversed, so the two TIMs oppose each other (Figure 3.21). A pair of fully compliant slider–crank mechanisms convert the
linear output of the TIMs to rotation. The slider–crank mechanism is converted to a compliant mechanism by rigid-body replacement synthesis: the coupler link is replaced with a fixed–guided flexible segment. The crank does not need a pin because of the antisymmetry of the design. The slider–crank mechanisms are oriented such that the flexible segments are aligned with the direction of the coarse motion. When the first stage moves, any friction between the second stage and the substrate must be reacted out through the flexible segments. The flexures deflect less and are less likely to break if this load is applied axially rather than transversely. Two configurations of the rotational stage are investigated. Figure 3.22a illustrates a short flexure connected to the near corner of the rotating stage. It is stiff in bending not only because it is short, but also because the deformed shape must conform to the second bending mode to accommodate the lateral motion. A
longer beam connected to the far corner is much less stiff in bending (Figure 3.22b). The flexure operates in tension to avoid possible contact with the near corner of the rotating stage, even though this causes stress stiffening.
The major components of the nanopositioners are analyzed to increase the probability of successful system-level operation. The ATIMs must switch the bistable mechanisms between states. The bistable mechanisms must exert a reasonable force on the electrical contacts to ensure good conductivity and to hold the first stages in place while the second stages move. The TIMs that operate the second stages must have the intended 5-µm range. In the cases of NanoTran 3 and the rotational nanopositioner, the TIMs must provide sufficient force to drive the amplifier and the compliant slider–crank mechanisms.

The general characteristics of the analytical models are presented first. Then the specific objectives, methods, and results of the analyses of the nanopositioner components are explained. The analyses of the coarse-motion stages are discussed before those of the fine-motion stages. The final section of this chapter covers the analysis of the second stage of the rotational nanopositioner.
4.1 Analytical Models

Both thermal and mechanical analyses are performed on the nanopositioner components. The objectives of the thermal analyses are: (1) find the relationship between electric current and beam temperature in the thermal actuators, and (2) identify the maximum current at which the actuators may be operated reliably. The mechanical analyses predict the displacements, forces, and stresses that occur in the actuators, bistable mechanism, amplifier mechanism, and rotating stage. The following sections provide details about the thermal and mechanical models that apply to all of the analyses.

4.1.1 Thermal Model

Christian Lott developed a transient heat transfer model for the TIM consisting of one pair of expansion beams [6,76]. Figure 4.1 illustrates the model with dimensions and node numbers that are specific to the TIM that controls the second stages of NanoTran 1, NanoTran 2, and the rotational nanopositioner. Nodes were placed at 10-µm increments along the expansion beams, shuttle, and surrounding material. One-dimensional finite difference equations for the nodal temperatures were derived from the law of conservation of
energy. The equations accounted for heat transfer by conduction to the substrate and radiation to the surroundings. The substrate was assumed to maintain a constant temperature because of its large mass. The equations for the spatial temperature distribution were evaluated at discrete time increments. The nodal temperatures at each succeeding time step were defined explicitly in terms of the temperatures of the same and adjacent nodes at the previous time step. Temperature-dependent material properties were evaluated at the previous time. The solution was carried out iteratively with time steps of 1 µs until the temperatures converged to the steady state. The length increment was small enough to resolve the spatial temperature distribution yet large enough to yield reasonable computation time. The time step had to be sufficiently small to ensure the stability of the iterative solution.

The material properties for the thermal analyses are listed in Table 4.1. The empirical relation for the thermal conductivity of polysilicon was derived as a curve fit to measurements made at temperatures up to 450 °C (723 K) [104]. The data and the empirical relation are plotted in Figure 4.2. The thermal analyses involve temperatures up to 900 °C (1173 K). The empirical relation is employed at these elevated temperatures because it is more accurate than the room-temperature thermal conductivity. The extrapolation is justified by comparing the empirical relation to experimental data [107] for pure (undoped) silicon (Figure 4.2). Although the thermal conductivity of polysilicon is not equal to that of pure silicon, the comparison reveals that the empirical relation follows the correct trend up to the melting temperature.

The resistivity of polysilicon varies approximately linearly with temperature (Figure 4.3). Lott measured the room-temperature resistivity (3.4×10⁻⁵ Ωm) directly and
<table>
<thead>
<tr>
<th>Property</th>
<th>Value or Temperature-Dependent Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity of Polysilicon [104]</td>
<td>( [1.4 \times 10^{-2} - 1.0 \times 10^{-5} T + 9.0 \times 10^{-8} T^2 - 2.2 \times 10^{-11} T^3]^{-1} ) ( \text{W/m K} ) for Celsius temperature ( T &lt; 450 \text{ °C} )</td>
</tr>
<tr>
<td>Resistivity of Polysilicon [6]</td>
<td>( 3.4 \times 10^{-2} \left( 1 + 1.25 \times 10^{-3} \frac{1}{\text{°C}} (T - T_r) \right) ) ( \Omega \text{m} ) for temperature ( T ) and ambient temperature ( T_r ) in Celsius</td>
</tr>
<tr>
<td>Absorptivity of Polysilicon [105]</td>
<td>0.6</td>
</tr>
<tr>
<td>Density of Single-Crystal Silicon [106]</td>
<td>( 2330 ) ( \text{kg/m}^3 )</td>
</tr>
<tr>
<td>Specific Heat of Single-Crystal Silicon [6]</td>
<td>( 705 ) ( \text{J/kg K} )</td>
</tr>
<tr>
<td>Thermal Conductivity of Single-Crystal Silicon [107]</td>
<td>( 150 ) ( \text{W/m K} )</td>
</tr>
<tr>
<td>Thermal Conductivity of Silicon Nitride [105]</td>
<td>( 2.25 ) ( \text{W/m K} )</td>
</tr>
</tbody>
</table>
obtained the temperature coefficient from published literature [6]. The absorptivity of polysilicon (0.6) was also taken from an earlier publication [105]. The density and specific heat of polysilicon are assumed to equal those of pure silicon at room temperature [6,106]. The thermal conductivities of single-crystal silicon and silicon nitride are assumed to remain constant at the room-temperature values [105,107]. The ambient temperature is 22 °C in all of the analyses.

The primary limitation on the range of motion of a TIM is the degradation of mechanical properties that occurs at high temperatures; the maximum stress is usually well below the strength of polysilicon. The performance of numerous TIMs has been observed to deteriorate after heating the expansion beams to the temperature at which they emit visible light. While validating the thermal model, Lott observed that radiation from a particular TIM became visible at an input current of 5.75 mA; the thermal model predicted

Figure 4.3 Empirical relation for the resistivity of polysilicon

![Graph showing the resistivity of polysilicon vs. temperature](image)

- Resistivity (10^-6 Ω m)
- Temperature (K)

Obtained the temperature coefficient \(1.25 \times 10^{-3} \frac{1}{°C}\) from published literature [6]. The absorptivity of polysilicon (0.6) was also taken from an earlier publication [105]. The density and specific heat of polysilicon are assumed to equal those of pure silicon at room temperature [6,106]. The thermal conductivities of single-crystal silicon and silicon nitride are assumed to remain constant at the room-temperature values [105,107]. The ambient temperature is 22 °C in all of the analyses.

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that the peak temperature in the expansion beams was 864 °C for the given current [6]. In the present research, 900 °C is assumed to be the maximum temperature at which a TIM may be operated reliably. The safe operating limit is defined as the current for which the peak temperature approaches but does not exceed 900 °C.

The thermal behavior of the nanopositioners is modeled in vacuum conditions because the tests are to be performed in the vacuum chamber of an SEM. In vacuum, there is no conduction of heat through air to the substrate. The only means of conducting heat to the substrate is through the polysilicon beams. Some heat is radiated to the substrate and to the surroundings. When thermal actuators do operate in atmospheric conditions, conduction through the air accounts for a significant portion of the total rate of heat transfer. Therefore, thermal actuators require less current to reach a particular temperature in vacuum than in air.

4.1.2 Mechanical Models

Two types of models are employed for the mechanical analyses: pseudo-rigid-body models and finite element models (FEMs). The PRBMs result in explicit equations that are easily evaluated. The FEMs are generally more accurate but require iteration to arrive at a solution. Table 4.2 gives the properties of polysilicon for the mechanical analyses. The empirical relation for the coefficient of thermal expansion [108] is plotted in Figure 4.4. The elastic modulus and tensile strength depend on fabrication process parameters, and a wide range of values have been published. The values that were selected were measured with polysilicon films similar to those produced by MUMPs [4,109].
The finite element models discussed in this chapter are all built and solved with ANSYS [110], which is a commercial software package for finite element analysis (FEA). The commands that build, mesh, and solve each of the models are stored in text files and executed as batches. The commands for a few of the FEMs are listed in Appendix A. All of the models are meshed with two-dimensional beam elements because the compliant members are slender; the aspect ratios of the flexible segments range from 30 to 70. The

\[ C_1 \left[ 1 - e^{-C_2(T - C_3)} \right] + C_4 T \times 10^{-6} \frac{1}{K} \]

where \( C_1 = 3.725 \), \( C_2 = 5.88 \times 10^{-3} \), \( C_3 = 124 \), \( C_4 = 5.548 \times 10^{-4} \), and \( T \) is the Kelvin temperature (300 K < \( T < 1500 \) K).

**TABLE 4.2** Material Properties of Polysilicon for the Mechanical Analyses

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>( C_1 \left[ 1 - e^{-C_2(T - C_3)} \right] + C_4 T \times 10^{-6} \frac{1}{K} ) where ( C_1 = 3.725 ), ( C_2 = 5.88 \times 10^{-3} ), ( C_3 = 124 ), ( C_4 = 5.548 \times 10^{-4} ), and ( T ) is the Kelvin temperature (300 K &lt; ( T &lt; 1500 ) K)</td>
</tr>
<tr>
<td>Poisson’s Ratio [4]</td>
<td>0.22</td>
</tr>
<tr>
<td>Tensile Strength [109]</td>
<td>3.2 GPa</td>
</tr>
</tbody>
</table>
meshes are refined until doubling the number of elements changes the results by less than 0.1%. The models solve quickly enough that sophisticated mesh optimization is not necessary; elements are uniformly spaced along individual beams, with shorter elements on beams that experience greater bending strain. Large deflections are anticipated in all of these analyses; therefore, the full Newton–Raphson nonlinear solution method is invoked within ANSYS. The sparse direct equation solver is employed at each iteration, and the stiffness matrix is updated at each iteration with terms that account for stress stiffening.

4.2 Coarse-Motion Stages

The first objective in analyzing the coarse-motion stages is to determine whether the ATIMs are able to actuate the bistable mechanisms. The second is to determine the displacement range of the coarse-motion stage for each nanopositioner and the force that it applies to the stop blocks it encounters in its second position. The thermal analysis of the ATIM is discussed first, followed by the mechanical analyses of the bistable mechanism and ATIM. Finally, the predictions for the bistable mechanism and ATIM are compared and conclusions are drawn.

4.2.1 Thermal Analysis

The thermal analysis of the TIM that operates the ATIM also applies to the second stage of NanoTran 3, which employs the same TIM. The finite difference model for this TIM differs only slightly from the illustration in Figure 4.1: the shuttle is smaller, so there are 2 nodes instead of 4 on the shuttle, and the entire model has 62 nodes. Table 4.3 lists the values of the model parameters. The entire TIM has 16 expansion beams on each side of the
shuttle, so it draws 16 times more current than the single pair of beams in the model. The finite difference model requires the length of the expansion beams to be an integer multiple of the node spacing (10 µm), so it is set to 200 µm instead of the design length of 205 µm. Similarly, the length of the shuttle segment has to be rounded to 10 µm, even though it is 11 µm long in the design. This discretization has a minor adverse effect on the accuracy of the analysis. The widths of the shuttle and anchored pads in the model are equal to the average distance between the expansion beams. In the actual device, the shuttle and pads are large objects that link all of the expansion beams.

Although the steady-state results are sufficient for the present research, the transient temperatures are useful as evidence of convergence. A step input of 25.7 mA was applied to the model to test convergence. With a single, 1.8 GHz processor, the model required 75 minutes to evaluate the solution up to 100 ms and only 27 minutes to run the solution to 50 ms. The maximum temperature in the model is plotted against time in Figure 4.5. The temperature at 50 ms is 0.06% lower than the temperature at 100 ms;

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams on each side of the shuttle</td>
<td>$16$</td>
<td></td>
</tr>
<tr>
<td>Number of nodes</td>
<td>$62$</td>
<td></td>
</tr>
<tr>
<td>Node spacing</td>
<td>$10\ \mu m$</td>
<td></td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>$L_e$</td>
<td>$200\ \mu m$</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>$w_e$</td>
<td>$3\ \mu m$</td>
</tr>
<tr>
<td>Shuttle length</td>
<td>$L_s$</td>
<td>$10\ \mu m$</td>
</tr>
<tr>
<td>Shuttle width</td>
<td>$w_s$</td>
<td>$10\ \mu m$</td>
</tr>
<tr>
<td>Pad length</td>
<td>$L_p$</td>
<td>$100\ \mu m$</td>
</tr>
<tr>
<td>Pad width</td>
<td>$w_p$</td>
<td>$10\ \mu m$</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>$t$</td>
<td>$3.5\ \mu m$</td>
</tr>
</tbody>
</table>
therefore, satisfactory results may be obtained by modeling only the first 50 ms of the transient response. The thermal analyses at other current levels were carried out to 50 ms. Figure 4.6 shows the maximum-temperature transients for various currents. The steady-state temperatures are lower and the solutions converge more quickly with less current.

The distribution of temperature across the model at 50 ms is plotted in Figure 4.7 for each of the currents for which the temperature transients were plotted (Figure 4.6). The maximum temperature occurs at the shuttle because the primary mode of heat transfer is conduction through the expansion beams. The maximum temperature in the TIM with an input of 25.7 mA is 868 °C. If the current is increased to 25.8 mA, the maximum temperature exceeds 900 °C, so 25.7 mA is taken as the safe operating limit. The thermal model predicts a voltage of 3.4 V across the TIM at the safe operating limit; the steady-state power consumption is 88 mW.
There are four ATIMs that must be actuated simultaneously to move the first stage of NanoTran 1 in each direction, and there are two TIMs in each ATIM, so there are a total of eight TIMs connected in parallel. The first stage of NanoTran 1 is predicted to require

Figure 4.6  Maximum-temperature transients for the TIM in the ATIM and NanoTran 3 at various currents

Figure 4.7  Steady-state temperature distributions across the TIM in the ATIM and NanoTran 3 for various currents
at most 206 mA at 3.4 V, or 707 mW of power, to operate in a vacuum over its full range of motion. NanoTran 2, NanoTran 3, and NanoTran 4 have two parallel ATIMs on each end of the first stage. The first stages of these mechanisms are expected to draw 103 mA of current, also at 3.4 V, and 354 mW of power at the safe operating limit. The second stage of NanoTran 3 is driven by two TIMs which are connected in parallel. The maximum anticipated electrical requirements are 51.4 mA, 3.4 V, and 177 mW.

The finite element model for NanoTran 3 imports the complete steady-state temperature distribution and applies a unique temperature to each node. To simplify the analysis of the ATIM, an equivalent uniform temperature is selected that results in the same thermal expansion. The uniform temperature is applied to all of the nodes in the expansion beams of the ATIM finite element model. The average thermal strain ($\epsilon_{th}$) is computed from the temperature distribution. It is related to the uniform temperature by

$$\epsilon_{th} = (T_u - T_r)\alpha(T_u)$$

(4.1)

The unknown uniform temperature is $T_u$, the ambient temperature is $T_r$, and $\alpha(T_u)$ is the temperature-dependent expression for the coefficient of thermal expansion (Table 4.2) evaluated at the uniform temperature. Equation 4.1 is solved by Newton’s method to obtain the uniform temperature. For the TIM in the ATIM, a uniform temperature of 537 °C yields the same thermal strain in the expansion beams as the highest temperature distribution in Figure 4.7.

4.2.2 Mechanical Analysis—Bistable Mechanism

The bistable mechanism is fabricated with low internal stress, and when it is released it moves slightly to relieve internal stresses. Then it is in its first stable equilibrium position.
In NanoTran 1, NanoTran 2, and NanoTran 3, the bistable mechanism comes to rest against stiff blocks or electrical contacts in its second position; in these devices the placement of the stops determines the range of the first stage. A high contact force results in low contact resistance and allows the second stage to apply a high force to the object being moved. The contact force may be maximized by placing the block at the correct distance from the first stable equilibrium position. In NanoTran 4, the motion of the bistable mechanism is not limited: the range of the first stage is the distance between the stable equilibrium positions.

A finite element model of one buckling beam is created with 140 elements (Figure 4.8). The model parameters are listed in Table 4.4. The anchored ends of the vertical beam (A and B in Figure 4.8) are modeled with all three planar degrees of freedom fixed ($x$, $y$, and $\theta_z$). The shuttle is modeled by constraining translation in the $x$ direction and rotation about the $z$ axis at the end of the buckling beam (C in Figure 4.8). The shuttle is displaced incrementally through the full range of the bistable mechanism; the force acting on the shuttle and the maximum tensile stress in the buckling beam are reported at each displacement. The force calculated by the model is multiplied by the number of
buckling beams (two) to obtain the force for the entire mechanism. The stable and unsta-
ble equilibrium positions are determined by removing the \( y \)-displacement constraint from
the end of the buckling beam and allowing the finite element solution to converge to the
equilibrium position. Counter-intuitively, the solution converges to the unstable equilib-
rium position as readily as to the second stable equilibrium position if the displacement is
reasonably close to the equilibrium position when the constraint is removed. The Newton–
Raphson solution algorithm uses the stiffness matrix to find the shuttle displacement for
which the reaction force is zero [111]. It follows the derivative of the force–displacement
curve to the nearest root. It does not look for a minimum of potential energy. The stiffness
(i.e. the derivative) is negative at the unstable equilibrium position, but the solver still con-
verges.

**TABLE 4.4** Parameters of the Finite Element Model for the Bistable Mechanism

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of buckling beams in the entire mechanism</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Segment 1 length</td>
<td>( L_1 )</td>
<td>64.2 ( \mu m )</td>
</tr>
<tr>
<td>Segment 1 width</td>
<td>( w_1 )</td>
<td>3.5 ( \mu m )</td>
</tr>
<tr>
<td>Segment 2 length</td>
<td>( L_2 )</td>
<td>95.7 ( \mu m )</td>
</tr>
<tr>
<td>Segment 2 width</td>
<td>( w_2 )</td>
<td>2.5 ( \mu m )</td>
</tr>
<tr>
<td>Segment 2 angle</td>
<td>( \theta_2 )</td>
<td>7°</td>
</tr>
<tr>
<td>Segment 3 length</td>
<td>( L_3 )</td>
<td>146.4 ( \mu m )</td>
</tr>
<tr>
<td>Segment 3 width</td>
<td>( w_3 )</td>
<td>10 ( \mu m )</td>
</tr>
<tr>
<td>Segment 3 angle</td>
<td>( \theta_3 )</td>
<td>6°</td>
</tr>
<tr>
<td>Segment 4 length</td>
<td>( L_4 )</td>
<td>77.3 ( \mu m )</td>
</tr>
<tr>
<td>Segment 4 width</td>
<td>( w_4 )</td>
<td>2.5 ( \mu m )</td>
</tr>
<tr>
<td>Segment 4 angle</td>
<td>( \theta_4 )</td>
<td>7°</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>( t )</td>
<td>3.5 ( \mu m )</td>
</tr>
</tbody>
</table>
Figure 4.9 is the force–displacement relation for the bistable mechanism; the equilibrium positions are labeled. The maximum tensile stress of 1.02 GPa occurs at a displacement of 28.3 µm, which is close to the unstable equilibrium position (30.7 µm). The maximum contact force for one bistable mechanism is 31 µN; it may be achieved by placing the stop blocks or electrical contacts 46.5 µm from the first stable equilibrium position. In NanoTran 1, the electrical contacts are placed at a displacement of 46 µm; the four bistable mechanisms are predicted to apply 62 µN to each of the two electrical contacts. NanoTran 2 has two bistable mechanisms and two electrical contacts; the first-stage range is extended to 52 µm, which reduces the predicted force to 25 µN per electrical contact. Although NanoTran 3 does not have electrical contacts, the contact force is important for locating the first stage precisely; the single bistable mechanism travels 52 µm and exerts a
force of 25 µN on the stop block. The first stage of NanoTran 4 has a range of 57.6 µm and a stiffness of $13 \frac{\mu N}{\mu m}$ in the second stable equilibrium position.

### 4.2.3 Mechanical Analysis—ATIM

The ATIM must provide sufficient force over a long enough distance to actuate the bistable mechanism and move the first stage across the substrate. The finite element model includes half of the ATIM: one TIM and one amplifying beam (Figure 4.10). Dimensions are given in Table 4.5. All degrees of freedom are fixed for the nodes at the outer ends of the expansion beams. The shuttle is only free to translate in the $y$ direction. The out-of-plane thickness of the single amplifying beam is multiplied by four to represent the four amplifying beams that are actually present in the half model. Similarly, the expansion
beams are lumped into four locations to simplify the model. The mesh is built with 588 elements to meet convergence requirements.

Temperatures from 150 °C to 537 °C are applied uniformly to the expansion beams. At each temperature, the shuttle displacement is first allowed to converge to the equilibrium position, then driven back to zero. The driving force and maximum tensile stress are reported at each displacement increment. This solution procedure generates the series of force–displacement relations in Figure 4.11; the forces have been doubled to represent the entire ATIM. In some nanopositioners the ATIM moves one bistable mechanism, but in others it actuates two simultaneously. Figure 4.11 illustrates the case of two bistable mechanisms.

The temperature of the ATIM increases monotonically when the current is applied (Figure 4.6). At any given temperature, the ATIM pulls the bistable mechanisms to the displacement where the forward force of the ATIM equals the opposing force of the bistable mechanisms. The equilibrium force–displacement pairs for temperatures of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams in the TIM</td>
<td>32</td>
<td></td>
<td>Number of amplifying beams in the half model</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>( L_{ex} )</td>
<td>14.3 µm</td>
<td>Segment 1 length</td>
<td>( L_{a1x} )</td>
<td>117.4 µm</td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>( L_{ey} )</td>
<td>204.5 µm</td>
<td>Segment 1 offset</td>
<td>( L_{a1y} )</td>
<td>4.1 µm</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>( w_e )</td>
<td>3 µm</td>
<td>Segment 1 width</td>
<td>( w_{a1} )</td>
<td>3 µm</td>
</tr>
<tr>
<td>TIM shuttle length</td>
<td>( L_s )</td>
<td>123 µm</td>
<td>Segment 2 length</td>
<td>( L_{a2x} )</td>
<td>215.9 µm</td>
</tr>
<tr>
<td>TIM shuttle width</td>
<td>( w_s )</td>
<td>11 µm</td>
<td>Segment 2 offset</td>
<td>( L_{a2y} )</td>
<td>7.5 µm</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>( t )</td>
<td>3.5 µm</td>
<td>Segment 2 width</td>
<td>( w_{a2} )</td>
<td>6 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Segment 3 length</td>
<td>( L_{a3x} )</td>
<td>118.2 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Segment 3 offset</td>
<td>( L_{a3y} )</td>
<td>4.1 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Segment 3 width</td>
<td>( w_{a3} )</td>
<td>3 µm</td>
</tr>
</tbody>
</table>
150 °C and 215 °C are marked with solid dots in Figure 4.11. As the temperature increases, the equilibrium displacement advances until the bistable mechanisms reach the unstable equilibrium position. At this point, the bistable mechanisms snap forward and lose contact with the ATIM. At 275 °C, the force curve of the ATIM exceeds the opposing force of the bistable mechanisms for all displacements up to the unstable equilibrium position, so the ATIM is predicted to be able to switch the two bistable mechanisms. The ATIM is capable of returning the bistable mechanisms to the first stable equilibrium position because the return motion requires less force over a shorter displacement. During the return motion, the ATIM acts against the negative portion of the force–displacement curve of the bistable mechanisms. The ATIM is expected to actuate a single bistable mechanism
(as in NanoTran 3) because the opposing force is half as great as that of two bistable mechanisms. The maximum tensile stress predicted by the FEM is 930 MPa; it occurs at a displacement of 24.2 µm with the uniform temperature equal to 537 °C. The ATIM has a range of 49.4 µm and a maximum tensile stress of 337 MPa when no load is attached.

4.3 Fine-Motion Stages

The four designs for the fine-motion stage are described sequentially. The safe operating limits are determined. The displacement–current relations and ranges are also predicted.

4.3.1 NanoTran 1 and NanoTran 2

The TIMs that control the fine-motion stages in NanoTran 1 and NanoTran 2 are analyzed with the same models because the lengths and angles of the expansion beams are identical. The models only include one expansion beam, so the different spacing of the beams and shape of the shuttle are neglected.

4.3.1.1 Thermal Model

The finite difference thermal model for the TIM in NanoTran 1 and NanoTran 2 has 64 nodes, as illustrated in Figure 4.1. The values of the model parameters for this TIM are listed in Table 4.6. The shuttle length was designed at 25 µm but rounded to 30 µm in the finite difference model. The transient response was modeled up to 100 ms with a current of 14.1 mA; it took 66 minutes of processor time. The maximum temperature throughout the model is plotted against time in Figure 4.12. The temperature at 50 ms is 0.41% less
than the final temperature, and the solution is obtained after only 25 minutes. Therefore, the thermal analyses at other currents are terminated at 50 ms (Figure 4.13).

Figure 4.12 Temperature transient for the TIM in NanoTran 1 and NanoTran 2 with a step input of 14.1 mA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams on each side of the shuttle</td>
<td>$n$</td>
<td>8</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>$N$</td>
<td>64</td>
</tr>
<tr>
<td>Node spacing</td>
<td>$D$</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>$L_e$</td>
<td>200 $\mu$m</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>$w_e$</td>
<td>3 $\mu$m</td>
</tr>
<tr>
<td>Shuttle length</td>
<td>$L_s$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Shuttle width</td>
<td>$w_s$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Pad length</td>
<td>$L_p$</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Pad width</td>
<td>$w_p$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>$t$</td>
<td>3.5 $\mu$m</td>
</tr>
</tbody>
</table>
Figure 4.13  Maximum-temperature transients for the TIM in NanoTran 1 and NanoTran 2 at various currents

Figure 4.14  Steady-state temperature distributions across the TIM in NanoTran 1 and NanoTran 2 for various currents

Figure 4.14 shows the steady-state temperature distributions for the same currents at which the temperature transients were plotted (Figure 4.13). The maximum temperature with 14.1 mA of current is 844 °C. The equivalent uniform temperature is 495 °C. An
additional 0.1 mA would raise the maximum temperature above 900 °C; therefore, the safe operating limit is 14.1 mA. The model predicts a voltage of 3.6 V and power consumption of 51 mW at the safe operating limit. NanoTran 1 and NanoTran 2 each have one TIM in the second stage. The electrical requirements for the TIM apply directly to both of these devices.

4.3.1.2 Mechanical Models

The TIM is analyzed with both the PRBM and FEA. Lott derived the PRBM for the TIM (Figure 4.15) [6]. It is fundamental to all of the PRBMs discussed in this chapter. The characteristic radius factor \( \gamma \) was chosen as 0.82 because the expansion beam experiences a strong compressive load. The torsional spring constants \( K \) and pseudo-rigid-body angle \( \Theta \) need not be determined because the PRBM does not account for stress stiffening, so force results cannot be obtained from the TIM PRBM.
The input to the PRBM is the uniform temperature from the thermal analysis \( T_u \).

The change in the total length of the expansion beam is

\[
\Delta L = \varepsilon_{th} L_e
\]

in which \( \varepsilon_{th} \) is the average thermal strain defined by Equation 4.1. The displacement of the shuttle was derived from the PRBM [6], and with some algebraic manipulation it is

\[
d_s = L_{ey} \left[ (1 - \gamma) \frac{\Delta L}{L_e} - \gamma + \sqrt{\gamma^2 + (2\gamma - 1) \left( \frac{L_{ex}}{L_{ey}} \right)^2 \left( \frac{\Delta L}{L_e} \right)^2 + 2\gamma \left( \frac{L_{ex}}{L_{ey}} \right)^2 \left( \frac{\Delta L}{L_e} \right) + \gamma^2} \right]
\]

With the parameters in Table 4.7 and \( T_u = 495 \, ^\circ\text{C} \), it evaluates to 6.9 µm.

A new finite element model was developed to apply the temperature distribution computed by the thermal model to a TIM (Figure 4.16). The node at the left end of the pad has all degrees of freedom fixed to simulate the substrate anchor. The node at the right end

---

**TABLE 4.7** Parameters of the Pseudo-Rigid-Body Model for the Second-stage TIM in NanoTran 1 and NanoTran 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion beam length</td>
<td>( L_{ex} )</td>
<td>200 µm</td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>( L_{ey} )</td>
<td>7 µm</td>
</tr>
<tr>
<td>Total expansion beam length</td>
<td>( L_e )</td>
<td>200.1 µm</td>
</tr>
<tr>
<td>Expansion beam angle</td>
<td>( \theta )</td>
<td>2°</td>
</tr>
<tr>
<td>Characteristic radius factor</td>
<td>( \gamma )</td>
<td>0.82</td>
</tr>
</tbody>
</table>

---

Figure 4.16 Finite element model for the TIM
of the shuttle is guided; its only degree of freedom is translation in the $y$ direction. The steady-state temperature distribution is applied to individual nodes in the pad, expansion beam, and TIM shuttle according to the $x$ coordinates of the nodes. The finite element model places more nodes along the expansion beam than the finite difference model in order to resolve the large deflection of the beam and satisfy the mesh refinement criterion. The element length is chosen such that the FEM has a node at the location of each node in the thermal model; the temperatures at these nodes are explicitly defined. The temperatures at the intermediate nodes are obtained by linear interpolation.

The FEM of the TIM in NanoTran 1 and NanoTran 2 has 112 elements; the parameter values are listed in Table 4.8. For an input current of 14.1 mA, the FEM predicts a displacement of 7.3 $\mu$m and a maximum tensile stress of 218 MPa, which is well below the tensile strength.

Figure 4.17 plots the displacement results from both the PRBM and the FEM against the current at which the temperature distributions were obtained with the thermal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams on each side of the shuttle</td>
<td>$n$</td>
<td>8</td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>$L_{ex}$</td>
<td>200 $\mu$m</td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>$L_{ey}$</td>
<td>7 $\mu$m</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>$w_e$</td>
<td>3 $\mu$m</td>
</tr>
<tr>
<td>Shuttle length</td>
<td>$L_s$</td>
<td>25 $\mu$m</td>
</tr>
<tr>
<td>Shuttle width</td>
<td>$w_s$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Pad length</td>
<td>$L_p$</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Pad width</td>
<td>$w_p$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>$t$</td>
<td>3.5 $\mu$m</td>
</tr>
</tbody>
</table>
model. The maximum difference between the PRBM and FEA results is 0.4 μm, or 5%.
The concordance of the two models supports the assumption of a uniform beam temperature in the PRBM. The results of the mechanical analyses indicate that the displacements of the second stages of NanoTran 1 and NanoTran 2 may be expected to exceed the 5-μm goal without breaking or melting the actuators.

4.3.2 NanoTran 3

The second-stage TIM in NanoTran 3 is identical to the TIM in the ATIM, for which the thermal analysis was presented in Section 4.2.1. For reference, the electrical requirements of NanoTran 3 are predicted to be 51.4 mA, 3.4 V, and 177 mW at the safe operating limit. The mechanical analysis is performed with a PRBM and an FEM.

The PRBM of NanoTran 3 is composed of the TIM PRBM (Figure 4.15) and the amplifier mechanism PRBM (Figure 4.18). The output displacement of the TIM PRBM is

![Figure 4.17 Displacement–current relations for the TIM in NanoTran 1 and NanoTran 2](image)
the input for the amplifier mechanism (Δx). The gap between the TIM and the first stage of NanoTran 3 is simulated by subtracting 0.4 μm from the TIM displacement. The displacement of the second stage of NanoTran 3 is labeled $d_s$ in Figure 4.18. The parameter values for both parts of the model are listed in Table 4.9. The characteristic radius factor ($\gamma$) is the same for the amplifier mechanism as for the TIM because the load conditions are similar.

**TABLE 4.9 Parameters of the Pseudo-Rigid-Body Model for NanoTran 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion beam length</td>
<td>$L_{ex}$</td>
<td>204.5 μm</td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>$L_{cy}$</td>
<td>14.3 μm</td>
</tr>
<tr>
<td>Total expansion beam length</td>
<td>$L_e$</td>
<td>205.0 μm</td>
</tr>
<tr>
<td>Expansion beam angle</td>
<td>0</td>
<td>4°</td>
</tr>
<tr>
<td>Amplifying beam length</td>
<td>$L_{ay}$</td>
<td>199 μm</td>
</tr>
<tr>
<td>Amplifying beam offset</td>
<td>$L_{ax}$</td>
<td>7 μm</td>
</tr>
<tr>
<td>Total amplifying beam length</td>
<td>$L_a$</td>
<td>199.1 μm</td>
</tr>
<tr>
<td>Amplifying beam angle</td>
<td>0</td>
<td>2°</td>
</tr>
<tr>
<td>Characteristic radius factor</td>
<td>$\gamma$</td>
<td>0.82</td>
</tr>
</tbody>
</table>
The amplifier is similar to a TIM except that it receives a mechanical rather than an electrical input. The kinematic analyses of the amplifier PRBM and TIM PRBM differ because the amplifier beams do not increase in length. The relationship between the input and output displacements is derived in a straightforward manner. Summing the components of the link lengths in the $x$ and $y$ directions yields two equations that relate the input and output displacements to the model geometry:

\[
\Delta x + \frac{1-\gamma}{2} L_{ax} + \gamma L_a \cos(\theta + \Theta) + \frac{1-\gamma}{2} L_{ax} - L_{ax} = 0 \tag{4.4}
\]

\[
\frac{1-\gamma}{2} L_{ay} + \gamma L_a \sin(\theta + \Theta) + \frac{1-\gamma}{2} L_{ay} - L_{ay} - d_s = 0 \tag{4.5}
\]

With algebraic manipulation and some trigonometric substitutions, the output displacement is obtained as a function of the input displacement.

\[
d_s = \gamma L_{ay} \left( \frac{\Delta x + \frac{2 L_{ax} \Delta x}{\gamma L_{ay}} \left( \frac{\Delta x}{\gamma L_{ay}} \right)^2 - 1}{1} \right) \tag{4.6}
\]

For a uniform temperature of 537 °C, which corresponds to the safe operating limit, the TIM displacement (Equation 4.3) is 5.1 µm and the second stage is predicted to travel 33.6 µm.

The finite element model for the second stage of NanoTran 3 includes one TIM, half of the amplifier mechanism, and the flexures on the first stage that support the amplifier mechanism (Figure 4.19). The model parameters are given in Table 4.10. Sets of expansion beams, amplifying beams, and flexures are lumped together by stacking them in the direction normal to the plane, as in the ATIM FEM. The left end of the pad is fully constrained. The TIM shuttle translates in the $y$ direction, and the second stage moves in
the \( x \) direction. The end of the flexure is free to move with the first stage in the \( x \) direction, but it is constrained against translation in the \( y \) direction and rotation. There are a total of 353 elements in the model. The nodal temperatures are applied in the same manner as in the TIM FEM (Figure 4.16). The elements that make up the expansion beam are 2 \( \mu \text{m} \)

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**Figure 4.19** Finite element model for NanoTran 3

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**TABLE 4.10** Parameters of the Finite Element Model for NanoTran 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams in the TIM</td>
<td></td>
<td>32</td>
<td>Number of amplifying beams in the half model</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>( L_{ex} )</td>
<td>204 ( \mu \text{m} )</td>
<td>Amplifying beam length</td>
<td>( L_{ay} )</td>
<td>199 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>( L_{ey} )</td>
<td>14.3 ( \mu \text{m} )</td>
<td>Amplifying beam offset</td>
<td>( L_{ax} )</td>
<td>7 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>( w_e )</td>
<td>3 ( \mu \text{m} )</td>
<td>Amplifying beam width</td>
<td>( w_a )</td>
<td>3 ( \mu \text{m} )</td>
</tr>
<tr>
<td>TIM shuttle length</td>
<td>( L_s )</td>
<td>11 ( \mu \text{m} )</td>
<td>Number of flexures in the half model</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>TIM shuttle width</td>
<td>( w_s )</td>
<td>30 ( \mu \text{m} )</td>
<td>Flexure length</td>
<td>( L_f )</td>
<td>200 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Pad length</td>
<td>( L_p )</td>
<td>100 ( \mu \text{m} )</td>
<td>Flexure width</td>
<td>( w_f )</td>
<td>3 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Pad width</td>
<td>( w_p )</td>
<td>30 ( \mu \text{m} )</td>
<td>Out-of-plane thickness</td>
<td>( t )</td>
<td>3.5 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>
long, so every fifth node in the FEM aligns with one of the nodes in the finite difference model, where temperature results are available. The length of the expansion beam is rounded to 204 µm because that is an integer multiple of the element length.

There is not a gap between the TIM and the amplifier mechanism in the FEM; it is simulated by displacing the TIM 0.4 µm away from the amplifier before increasing the temperature of the expansion beam. With 51.4 mA of current, the displacement of the second stage is 30.5 µm. The maximum tensile stress is 931 MPa. Without the simulated gap, the displacement is 32.2 µm and the stress is 981 MPa, so the gap has a small effect on the predictions.

Both of the mechanical models are evaluated over a range of currents. The results of the PRBM and FEA for the amplifier mechanism alone are compared in Figure 4.20. The input displacement from the TIM is plotted on the abscissa; the output displacement is zero until the TIM displacement exceeds the length of the gap. The maximum difference
between the results of the PRBM and the FEM is 0.3 µm, or 4%. This observation confirms that the PRBM models nonlinear deflection well and that the finite element mesh is sufficiently fine.

The displacement–current relations predicted by the PRBM and FEA for the second stage of NanoTran 3 are plotted in Figure 4.21. The second stage does not move until the TIMs contact the amplifier mechanism, at about 24 mA. The FEM predicts less displacement than the PRBM because it accounts for the force acting against the TIM, which is the force required to buckle the amplifying beam and bend the flexures. The TIM does not move as far because of the opposing force; therefore, the input to the amplifier mechanism is not as great, and the output displacement is significantly reduced. The FEM is more accurate than the PRBM because it accounts for stress stiffening.

Figure 4.21 Displacement–current relations for NanoTran 3
4.3.3 NanoTran 4

The fourth nanopositioner design, NanoTran 4, employs the bistable mechanism as a thermal actuator. The mechanical analysis of the bistable mechanism is extended to determine the feasibility of the concept. A thermal analysis is not performed, but a uniform beam temperature of 495 °C is assumed to be safe because the geometry of the bistable mechanism is somewhat similar to that of the second-stage TIM in NanoTran 1. The uniform temperature is applied to the FEM after it has converged to the second stable equilibrium position at a distance of 57.6 µm from the first stable equilibrium position. Thermal strain causes the equilibrium position to shift 5.5 µm to a total displacement of 63.1 µm. It is significant that the mechanism remains bistable as it is heated and that the displacement increases with temperature. The maximum tensile stress (1.02 GPa) occurs before the bistable mechanism reaches the second stable equilibrium position (page 83). The highest stress calculated during actuation is 715 MPa.

NanoTran 4 is expected to function as a nanopositioner with independent coarse and fine motion control, even though it only has one stage. It has an advantage because there is continuous material from the substrate to the shuttle: there are no gaps to close. The low stiffness of the bistable mechanism in the second stable equilibrium position is a disadvantage; it may be seriously impeded by friction.

4.4 Rotating Stage

The first stage of the rotational nanopositioner is identical to that of NanoTran 2. The second stage is operated by compact TIMs, as in NanoTran 2, but each of the TIMs is
attached to a compliant slider–crank mechanism. The analysis of the TIM was explained in Section 4.3.1. The slider–crank mechanism is analyzed with a PRBM (Figure 4.22) to determine its angular range. Values of the model parameters are listed in Table 4.11. In Figure 4.22, $d_s$ is the linear displacement of the TIM and $\Delta \theta$ is the output rotation. The value 0.85 is selected for the characteristic radius factor ($\gamma$) because it is reasonably accurate for a wide variety of load conditions [97]. This is a simple choice and adequate for the intended accuracy of the model. The rotational range of the PRBM is determined by kine-

**TABLE 4.11** Parameters of the Pseudo-Rigid-Body Model for the Compliant Slider–Crank Mechanism

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible coupler length</td>
<td>$L_c$</td>
<td>150 $\mu$m</td>
</tr>
<tr>
<td>Crank $x$ component</td>
<td>$C_1$</td>
<td>19.5 $\mu$m</td>
</tr>
<tr>
<td>Crank $y$ component</td>
<td>$C_2$</td>
<td>98.5 $\mu$m</td>
</tr>
<tr>
<td>Characteristic radius factor</td>
<td>$\gamma$</td>
<td>0.85</td>
</tr>
</tbody>
</table>
matics, not the stiffness of the compliant segment, because the input is a displacement rather than a force. Therefore, the torsional spring constant (\( K \)) does not need to be evaluated.

The link lengths of the PRBM \((r_1, \ldots, r_4)\) are defined by

\[
\begin{align*}
    r_1 &= \frac{1 + \gamma}{2} L_c - C_1 + d_s \\
    r_2 &= \sqrt{\left(C_1 - \frac{1 + \gamma}{2} L_c\right)^2 + C_2^2} \\
    r_3 &= \gamma L_c \\
    r_4 &= C_2
\end{align*}
\]

(4.7)

The angle of link 2 \((\theta_2)\) is derived from the law of cosines.

\[
\theta_2 = \cos^{-1}\left(\frac{r_1^2 + r_2^2 - r_3^2 - r_4^2}{2r_2\sqrt{r_1^2 + r_4^2}}\right) + \tan^{-1}\left(\frac{r_2}{r_1}\right)
\]

(4.8)

Equation 4.8 may also be obtained by solving the standard slider–crank equations [97]. As the TIM displacement increases from 0 to \(d_s\), the crank rotates through an angle of

\[
\Delta \theta = \theta_2\bigg|_{d_s = 0} - \theta_2\bigg|_{d_s}
\]

(4.9)

which is the rotational range. By Equation 4.3, the TIM displacement is 6.9 µm for a uniform temperature of 495 °C. The rotational range evaluates to 4.0° \((70 \times 10^{-3} \text{ rad})\).

In addition to the PRBM analysis, the rotational range and maximum tensile stress were evaluated by finite element analysis. The finite element model (Figure 4.23) includes one of the TIMs and a single slider–crank mechanism. The crank has a constraint that only allows it to rotate about the \(z\) axis. The expansion beams have fixed end constraints. Dimension values are provided in Table 4.12. In the FEM, the 16 expansion beams are...
lumped into four locations by stacking them in the out-of-plane direction. A uniform temperature of 495 °C is applied to the expansion beams. The model requires 260 elements for all the results to converge within 0.1%. The analysis predicts a range of 3.8° (66×10⁻³ radians) and a maximum tensile stress of 349 MPa, which is safely below the tensile strength of polysilicon. The range predicted by the PRBM differs from the FEA result by 6%.
4.5 Summary

The objectives of this research, as stated in Section 1.3, are to achieve a coarse-motion range of about 50 µm, a fine-motion range of at least 5 µm, and resolution below 25 nm. The analyses indicate that the nanopositioners will probably meet the objective for range. The electrical requirements should be within the capability of standard power supplies. The mechanisms are not likely to fail by fracture, but the thermal actuators may fail by melting if the current limits are exceeded.

**TABLE 4.12** Parameters of the Finite Element Model for the Rotational Nanopositioner

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expansion beams in the TIM</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Expansion beam length</td>
<td>( L_{ey} )</td>
<td>200 µm</td>
</tr>
<tr>
<td>Expansion beam offset</td>
<td>( L_{ex} )</td>
<td>7 µm</td>
</tr>
<tr>
<td>Expansion beam width</td>
<td>( w_e )</td>
<td>3 µm</td>
</tr>
<tr>
<td>Shuttle length</td>
<td>( L_s )</td>
<td>134 µm</td>
</tr>
<tr>
<td>Shuttle tail length</td>
<td>( L_{st} )</td>
<td>13 µm</td>
</tr>
<tr>
<td>Shuttle width</td>
<td>( w_s )</td>
<td>16 µm</td>
</tr>
<tr>
<td>Flexible coupler length</td>
<td>( L_c )</td>
<td>150 µm</td>
</tr>
<tr>
<td>Flexible coupler width</td>
<td>( w_c )</td>
<td>3 µm</td>
</tr>
<tr>
<td>Crank x component</td>
<td>( C_1 )</td>
<td>19.5 µm</td>
</tr>
<tr>
<td>Crank y component</td>
<td>( C_2 )</td>
<td>98.5 µm</td>
</tr>
<tr>
<td>Out-of-plane thickness</td>
<td>( t )</td>
<td>3.5 µm</td>
</tr>
</tbody>
</table>
This chapter discusses accuracy in position control and uncertainty in position measurement. Accuracy is a characteristic of the nanopositioners; measurement uncertainty determines the quality of the measurement process and the usefulness of all measured data. In Section 5.1, possible causes of position errors that occur while operating the nanopositioners are identified. Tests are outlined for measuring the accuracy of the nanopositioners. In Section 5.2, the sources of measurement uncertainty are investigated. The tests that were performed to quantify measurement uncertainty are explained and results are presented.

5.1 The Accuracy of a Positioning Device

Accuracy was defined in Chapter 1 as the absolute value of the position error (page 1). In the operation of a nanopositioner, a desired (or command) position is selected. The input corresponding to the command position is found from a calibration curve, which may be obtained through either analysis or experimentation. The input is applied to the actuators, and the nanopositioner moves. The position error is the difference between the desired and actual positions.
Accuracy has two components: *trueness* (or systematic error) and *precision* (or random error) [112]. The systematic component is constant in a series of repeated movements to the same position. The random component is different in each movement. The sources of systematic and random errors are discussed separately.

5.1.1 Trueness

Systematic errors are introduced in the design and operation of the nanopositioners. Assumptions that simplify the analytical models create a disparity between the predicted and actual performance. The modeling error affects the trueness of all devices that are fabricated from the same design.

During operation, factors such as the systematic error in the current source and Coulomb friction may influence trueness. The error in the current source may be determined with an ammeter. Friction is a disturbance force that the nanopositioners must overcome in order to reach the command position. The nanopositioners are designed with compliant mechanisms in order to minimize friction, but some contact with the substrate does occur. Friction resists the motion of the nanopositioner, so the actual position is less than the predicted position when moving forward and greater than the predicted position when moving backward. The difference between the positions reached by moving forward and backward to the same command position is hysteresis.

5.1.1.1 Hysteresis

A hysteresis test involves stepping the current from zero to the safe operating limit and back. The current levels for the reverse motion must be identical to those of the forward motion. The hysteresis at each level is
where \( p_f \) and \( p_r \) are the positions measured in the forward and reverse directions, respectively. Let the largest hysteresis observed over the course of the test be \( h_{\text{max}} \), and let the maximum displacement be \( d_{\text{max}} \). The hysteresis of the nanopositioner is expressed as a fraction of the range:

\[
H = \frac{h_{\text{max}}}{d_{\text{max}}} \cdot 100\% \quad (5.2)
\]

The hysteresis indicates the significance of friction with respect to the stiffness of the compliant mechanism that moves the second stages of the nanopositioners. Suppose an attractive force of constant magnitude, \( N \), pulls the second stage of a nanopositioner against the substrate. Let \( \mu_k \) be the kinetic friction coefficient. Then the friction force resisting motion is

\[
F = \mu_k N \quad (5.3)
\]

If the stiffness of the nanopositioner (\( k \)) is constant in the region near the command position, the second stage stops moving when it comes within a distance \( \varepsilon = \frac{F}{k} \) of the command position (\( p_c \)). For forward motion, the actual position is

\[
p_f = p_c - \varepsilon \quad (5.4)
\]

For reverse motion, the actual position is

\[
p_r = p_c + \varepsilon \quad (5.5)
\]

The absolute hysteresis is
Equation 5.6 shows that if friction cannot be prevented, the hysteresis may be reduced by increasing the stiffness of the nanopositioner.

Trueness improves significantly with calibration. When the experimental displacement–current relation is used to operate the device, the systematic errors from the analysis and current source are eliminated. Hysteresis may also be removed by referring to separate experimental data for forward and reverse operation. With calibration, the trueness of the nanopositioner approaches that of the measurement process. The calibration of the measurement process is discussed in Section 5.2.

5.1.1.2 Drift

A drift test measures the stability of a nanopositioner over time. The test is performed by applying a step input to the nanopositioner and measuring the position at regular intervals over a period of time, possibly until the position stops changing. The absolute drift of the nanopositioner at a particular time is given by

\[
D = p - p_1
\]  

(5.7)

where \( p \) is the instantaneous position and \( p_1 \) is the position at the beginning of the test. The result of interest may be the minimum time required for the position to converge to steady state within some tolerance; the drift measured at this time is termed the start-up drift. The nanopositioner is allowed to warm up for this length of time before use. If there is not a steady state, the drift may be reported for a time interval equal to the typical operation time of the nanopositioner.
Thermal drift is a gradual change in position that occurs as a result of a change in the temperature of the device or its surroundings. The temperature of the silicon chip rises above the ambient temperature as electrical power is dissipated by the thermal actuators. The increase in the temperature of the substrate causes the displacement of the nanopositioner to increase; the reason is as follows. As the substrate temperature rises, the steady-state temperatures of the actuators also rise such that the rate of heat transfer remains equal to the electrical power. As the temperature increases, the thermal conductivity of polysilicon decreases (Figure 4.2), resulting in a lower rate of conductive heat transfer and, consequently, a greater temperature difference between the actuators and the substrate. The increase in the temperature difference causes the nanopositioner to move forward. The mechanical response is amplified because the actuators, which are at 500 °C, have a greater coefficient of thermal expansion \( \left( 4.1 \times 10^{-6} \frac{1}{K} \right) \) than the substrate \( \left( 2.5 \times 10^{-6} \frac{1}{K} \right) \), which is at room temperature (Figure 4.4). The reduction in heat transfer and the increase in thermal expansion combine to augment the displacement of the nanopositioner.

Thermal actuators change permanently when they are operated near the melting temperature. They yield smaller displacements and move to a negative displacement when de-energized [65]. Permanent deformation may be prevented by operating well below the melting point.
5.1.2 Precision

Random variation in the dimensions and material properties of parts produced by surface micromachining also affects performance. All of the devices produced from a particular design have unique calibration curves whether they are fabricated in the same batch or in different batches. For a particular prototype, the dimensions and properties are fixed, and the uncertainty may be removed by calibration. The random uncertainty must be dealt with if tests are to be replicated on more than one prototype of the device.

Environmental factors introduce random position error during operation. Electrostatic charge in the device and in the substrate fluctuates randomly. It may exert sufficient force on the device to cause it to contact the substrate and develop friction. Fluctuation in the ambient temperature may affect the performance of the nanopositioners. The temperature of the silicon chip is expected to remain close to the ambient temperature [6], and, as was explained in Section 5.1.1.2, changes in the chip temperature affect the displacement of the nanopositioners.

5.1.2.1 Repeatability

The repeatability of a nanopositioner is the random error in the final position when the same step input is given multiple times. The position is measured with each repetition. The mean (μ) and standard deviation (σ) of the position measurements are computed. The repeatability is quantified in terms of a precision interval. The precision interval is defined as

$$\mu \pm t_{\nu, p} \sigma$$ (5.8)

where $t_{\nu, p}$ is obtained from the Student’s $t$ distribution [113,114]. The number of degrees
of freedom ($v$) is one less than the number of repetitions in the test, and $P$ is the probability. A probability of 95% was selected for this research. The precision interval is a symmetric region about the mean displacement in which a single additional repetition would be expected with 95% probability.

A repeatability test involves only one nanopositioner; it is performed in one location so that environmental factors remain essentially constant. Repeatability tests may be replicated with different devices of the same design and in different locations, in which case the precision of the nanopositioner is the Euclidean norm of the measured repeatabilities.

5.1.2.2 Resolution

The resolution is the smallest step that can be distinguished in the motion of a nanopositioner. Random uncertainty in the motion of the nanopositioner or the measurement process limits the resolution by masking the distinction between the positions before and after the step. The resolution of the power supply may also limit the resolution of the nanopositioner.

To measure the resolution of a nanopositioner, the input is increased by steps, and the position is measured ten times at each step. The position at each step is the mean of the ten measurements. The 95% precision interval about the mean quantifies the total uncertainty in the position, which is a composite of the uncertainties in the measurement and in the motion of the device. The size of each step is the difference between its mean position and that of the previous step. A step is considered to be resolved if the precision interval of that step does not overlap the precision interval of the previous step. The resolution mea-
measured in a single test is the average size of the steps that are resolved. The resolution of a nanopositioner is the smallest resolution measured in any test. Random position error limits resolution because if the precision intervals of two positions overlap, the measurements are not distinct, and it is not possible to predict with 95% probability that the input will result in one position and not the other.

If distinct steps are not observed in the position data, then the precision of the nanopositioner is limiting the resolution, and the current increment must be increased until the steps become distinct. If the steps are all distinct, the current increment may be decreased, unless it is already equal to the resolution of the power supply. If the widths of the precision intervals are equal to the repeatability of the measurement process, the resolution of the nanopositioner is masked by measurement uncertainty. The measurement process would need to be improved in order to correctly ascertain the resolution of the nanopositioner.

5.1.3 Experiments

Experiments were performed to quantify the resolution, repeatability, hysteresis, and thermal drift of the nanopositioners. Detailed procedures for each of these tests are provided in Appendix B. The results are presented in Chapter 6.

5.2 Measurement Uncertainty

Position measurements were obtained from images acquired with a scanning electron microscope. Figure 5.1 shows the SEM and the computer system that controls it. The SEM software included a ruler bar in each image and reported the length of the bar. The
nanopositioner operated inside the SEM vacuum chamber. An electrical interface mounted on the wall of the vacuum chamber enabled the nanopositioner to connect to an external power supply. Each image was recorded over a period of 64 s, and the settling time of a TIM in vacuum is on the order of 10 ms \cite{76}, so the SEM was limited to observing the steady-state positions of the nanopositioners.

5.2.1 Measurement Process

Figure 3.20 shows a portion of the second stage of NanoTran 3 and the ruler that served as a reference for position measurements. The images acquired by the SEM were analyzed numerically to measure the position of the moving object (the second stage) relative to the reference object (the ruler). The numerical procedure made it possible to measure the images consistently. Figure 5.2a is a single image from one of the repeatability tests. The finger on the second stage and a few fingers of the ruler are visible. The image was first
cropped to a convenient size that included straight portions of both the moving and reference objects (Figure 5.2b). The crop operation was performed in Adobe Photoshop [115]; the remainder of the image processing was accomplished with Matlab [116]. In Figure 5.2b, the moving object is on the left, and the reference object is on the right. The edges of the objects were aligned with the columns of the image. The grayscale values of the pixels in each column of the cropped image were averaged. The column averages are plotted against the column number in Figure 5.3a on a scale from 0 (black) to 1 (white).
The edges of the moving and reference objects appear as steep slopes in Figure 5.3a. The edges were identified by investigating the derivative of the grayscale value with respect to the column number (Figure 5.3b). The derivative was computed with a second-order central difference equation. The edge of the moving object is selected as an example to illustrate the method of locating an object. Figure 5.2c is an enlarged image of a few pixels near the edge of the moving object. The edge is characterized by a gradual shift from dark to light. Figure 5.4a shows the grayscale profile of the moving edge;
Figure 5.4b illustrates the method of identifying the moving edge from the derivative of the grayscale profile. A threshold value of the derivative (0.015 in this example) was chosen. Pixels for which the derivative was greater than the threshold were identified as belonging to the edge.

A linear fit equation for the pixels on the edge of the moving object was computed by the least squares method (Figure 5.4a). The equation for the grayscale value $g$ at column number $s$ is

$$g = ms + c \quad (5.9)$$

with coefficients $m$ and $c$. A benchmark grayscale value was chosen at approximately the mean grayscale value of the pixels that belonged to the edge. The location of the moving object ($s_m$) relative to the left side of the image was defined as the intersection of the linear fit equation (Equation 5.9) and the benchmark ($b$).

$$s_m = \frac{b - c}{m} \quad (5.10)$$

In this example, $m = 5.065 \times 10^{-2} \frac{1}{\text{pixel}}$, $c = -4.589$, $b = 0.55$, and $s_m$ evaluated to 101.5 pixels.

The reference object was located in the same manner as the moving object. The relative position of the second stage was

$$p = \frac{s_m - s_r}{f} \quad (5.11)$$

where $s_r$ was the location of the reference object and $f$ was a calibration factor relating the image unit (pixel) to a standard unit (micrometer). For the image in Figure 5.2b,
The second stage was the difference between the measured position and the average position with no current flowing through the TIMs. Appendix A includes a Matlab program that performs the image analysis described above.

The benchmarks for the moving and reference edges were not always equal due to the nature of the SEM imaging process. Benchmarks were chosen that were approximately half-way between the darkest and lightest pixels that belonged to the edges.

If the grayscale profile sloped downward at the edge of the moving object and upward at the edge of the reference object, raising the benchmarks would increase the distance measurement. In all the tests of the dual-stage nanopositioners, edges were selected for which the derivative had the same sign to minimize the sensitivity of measurements to the choice of the benchmark grayscale values.

The brightness of an SEM image depends in part on the amount of polysilicon that is visible. The brightness of the edges to be measured changes with the displacement of the nanopositioner and with time. In some of the tests the variations were substantial, and it became necessary to adjust the brightness and contrast of the images in order to obtain position measurements. In these cases the grayscale profiles were adjusted as part of the measurement process. Two regions of relatively uniform grayscale value were chosen in the images; one had a relatively low average grayscale value and the other had a relatively high average grayscale value. The surfaces of the moving object and the substrate met these criteria. The grayscale profiles of all of the images in a particular test were shifted and scaled vertically such that the two regions had the same average grayscale values in

\[ s_r = 606.4 \text{ pixels}, \quad f = 52.84 \frac{\text{pixels}}{\mu m}, \quad \text{and} \quad p = -9.557 \mu m. \]
all of the profiles. This adjustment made it possible for a single benchmark to intersect the edge of the moving object in all of the profiles. Without the adjustment, it would have been necessary to use a different benchmark for every measurement, which would have lessened the repeatability of the measurement process. The adjustment was only made in those tests for which it is explicitly stated in the results (Chapter 6).

The images for the tests of the dual-stage nanopositioners were taken at 5000 times magnification with a resolution of $1296 \times 968$ pixels. The calibration factor for all images acquired with these settings was calculated from the data collected for the repeatability tests of NanoTran 3 and NanoTran 4. The rulers adjacent to these devices were used as reference objects because the distances between the fingers remained constant. Four different rulers were measured; a short and a long measurement were taken from each, so the calibration was done with $n = 8$ unique features. The measured dimension of each feature was the average value obtained from ten images. The design dimensions $(d_i|_{i=1\ldots n})$ and measurements $(m_i|_{i=1\ldots n})$ are listed in Table 5.1. The relative error in each measured dimension was

<table>
<thead>
<tr>
<th>Feature</th>
<th>Design Dimension</th>
<th>Measured Dimension</th>
<th>Calibrated Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 µm</td>
<td>317.4 pixels</td>
<td>6.007 µm ±2.4 nm</td>
</tr>
<tr>
<td>2</td>
<td>6 µm</td>
<td>317.5 pixels</td>
<td>6.009 µm ±3.2 nm</td>
</tr>
<tr>
<td>3</td>
<td>7 µm</td>
<td>368.7 pixels</td>
<td>6.978 µm ±3.3 nm</td>
</tr>
<tr>
<td>4</td>
<td>7 µm</td>
<td>370.9 pixels</td>
<td>7.020 µm ±1.5 nm</td>
</tr>
<tr>
<td>5</td>
<td>12 µm</td>
<td>633.3 pixels</td>
<td>11.986 µm ±2.5 nm</td>
</tr>
<tr>
<td>6</td>
<td>12 µm</td>
<td>634.0 pixels</td>
<td>11.999 µm ±2.5 nm</td>
</tr>
<tr>
<td>7</td>
<td>13 µm</td>
<td>684.7 pixels</td>
<td>12.958 µm ±3.3 nm</td>
</tr>
<tr>
<td>8</td>
<td>13 µm</td>
<td>688.4 pixels</td>
<td>13.028 µm ±2.2 nm</td>
</tr>
</tbody>
</table>
The average error was set equal to zero.

\[ \frac{1}{n} \sum_{i=1}^{n} r_i = 0 \]  

(5.13)

The calibration factor that resulted in the least mean error was found by solving Equations 5.12 and 5.13.

\[ f = \frac{1}{n} \sum_{i=1}^{n} \frac{m_i}{d_i} \]  

(5.14)

The numerical value was \( f = 52.84 \text{ pixels/\mu m} \). The calibrated measurements in Table 5.1 include the 95% precision intervals of the measured dimensions.

Position measurements have systematic and random errors that must be determined experimentally. Measurement uncertainty must be reduced in order to determine the true capability of the nanopositioner. If the total error of the measurement process exceeds that of the nanopositioner, it will mask the true performance. The following sections discuss the tests that were performed to determine the uncertainty in the measurement process.

5.2.2 Systematic Uncertainty

The key to obtaining true measurements from scanning electron micrographs is to calibrate the images with a small object of known size. The calibration factor can be obtained on a routine basis from either an object of known size that is visible in the image or the
ruler bar provided by the software that controls the SEM, but both of these references must first be checked against a more accurate standard.

5.2.2.1 Calibration

Surface micromachined objects were used as standards for image calibration. The objects differed in size and shape from the geometry specified in the design drawings. The systematic and random components of the error were measured separately; the tests are described here.

The ratio of the finished size of the entire chip to the design size is the MUMPs scale factor. It is also the average ratio of the finished sizes of small features to their respective design dimensions. Error in the scale factor affects feature sizes systematically. The MUMPs scale factor was measured with a micrometer caliper under an optical microscope. The distances between objects in the four corners of the MEMS chip were measured and divided by the design dimensions. The average distance was 9.4 mm; the uncertainty in each measurement was estimated to be ±18 µm. The measured distances exceeded the design dimensions by 0.09% ±0.19%. The scale error was zero within experimental accuracy; therefore, the MUMPs scale was assumed to be accurate.

The nonlinearity of the surface-micromachining process is the random deviation of individual feature sizes from the overall pattern. Random error in features sizes may be attributed to the limited resolution of the lithography equipment and spatial variations in the etch rate. The linearity of MUMPs features was calculated from the measurements of the eight features that were used to calibrate the measurement process. The linearity error of the feature dimensions is plotted in Figure 5.5 with precision intervals to indicate mea-
measurement uncertainty. The precision intervals do not generally span zero, so there is definite nonlinearity in the feature dimensions. The linearity errors are all less than 0.4% of the design dimensions; therefore, surface micromachined objects are accurate enough to be used as standards for calibration.

The SEM ruler bar is especially valuable for calibrating images made at a different magnification or resolution (i.e. image size) than the settings for which the measurement process was calibrated from a physical standard. For images taken with a magnification of 5000 and a resolution of 1296 × 968 pixels, the SEM ruler bar indicates that the calibration factor is \( 52.40 \, \text{pixels} / \mu\text{m} \); this is 0.83% less than the calibration factor computed from measurements of surface-micromachined objects.

Figure 5.5 Linearity error of MUMPs feature dimensions
The widths of thin polysilicon beams are consistently produced at less than the design values. It is hypothesized that some over-etch of either the mask or the polysilicon occurs in MUMPs. Thin beams are fabricated about 0.5 µm narrower than the design width; large objects are affected less. To reduce the systematic error in the calibration factor due to over-etch, only features with equal widths were used for the calibration of the measurement process, and the dimensions were measured between edges of the features for which the derivative of the grayscale profile had the same sign.

5.2.2.2 Image distortion

Distortion of the images acquired by the SEM introduces systematic uncertainty to the measurement process. It usually takes the form of barrel distortion: points near the center of the image are magnified more than points near the edges [117]. The distortion is related to the angle at which the electron beam strikes the sample. The angle of incidence changes as the beam scans the sample and reaches a maximum at the perimeter of the image. At high magnification, the angle of incidence is small and the distortion is negligible. The distortion was quantified by measuring the period of a diffraction grating at various locations within the field of view. To investigate the distortion parallel and perpendicular to the scan direction, images were taken with the grating in both of these orientations (Figure 5.6). The period of the grating was measured at the center of each image, at the midpoints of the edges, and in the corners. Each measurement was the average of nine periods. The grating period was assumed to be constant throughout each image, and the measurement at the center was assumed to be accurate. The distortion was defined as the relative difference between the periods measured at a peripheral location and the center.
The maximum distortion was $-0.18\%$. However, the precision interval of every measurement included the true period, so the distortion was not statistically significant. The images in this test were taken at a magnification of 3000; the images for the accuracy tests were acquired at a higher magnification, so they also had negligible distortion.

5.2.2.3 Image drift

Processes that occur over long periods of time, such as the accumulation of electrostatic charge, may cause position measurements to drift. The stability of the measurement process was tested by measuring the distance between two fingers on the NanoTran 4 ruler for a period of 72 minutes. The drift of the measurement process is plotted in Figure 5.7. The slope of the least-squares fit line is $-2.7$ nm per hour. The largest drift measurement was $-3.5$ nm.

Figure 5.6 The SEM distortion was measured on images of a diffraction grating oriented (a) parallel and (b) perpendicular to the scan direction.
5.2.3 Random Uncertainty

Random error in measurements is caused by the limited resolution of the electron microscope and the digital image it creates. The random uncertainty of the measurement process was determined from four repeatability tests. The ruler on NanoTran 3 was measured in each test. The tests were performed on two different days; features with nominal dimensions of 6 µm and 12 µm were measured on each day. The precision intervals of the four tests are given in Table 5.2. The precision of the measurement process is the Euclidean norm of the repeatabilities: ±6.1 nm.

Figure 5.7 Drift of the measurement process
5.2.4 Focus Sensitivity

The sensitivity of position measurements to the focus of the SEM was investigated. The measurement process would be less accurate if the SEM were not focused properly because the edges of the features being measured would be wider and the grayscale profiles would have shallower slopes. The ruler on NanoTran 3 was imaged with the focal point of the electron beam above, at, and below the surface of the chip (Figure 5.8). The images were magnified 10 000 times. The errors in the measurements of these images are listed in Table 5.3. The nominal dimension of the feature that was measured was 6 µm.

![Figure 5.8](image)

**Figure 5.8** SEM images taken with the focal point (a) substantially above, (b) slightly above, (c) close to, (d) slightly below, and (e) substantially below the sample

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of Repetitions</th>
<th>Nominal Dimension</th>
<th>Precision Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31</td>
<td>6 µm</td>
<td>6.006 µm ±5.6 nm</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>12 µm</td>
<td>11.985 µm ±7.9 nm</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>6 µm</td>
<td>6.003 µm ±4.8 nm</td>
</tr>
<tr>
<td>4</td>
<td>41</td>
<td>12 µm</td>
<td>11.969 µm ±5.7 nm</td>
</tr>
</tbody>
</table>
Moderate error in the focus adjustment caused less than 0.2% error in the measurement process.

**TABLE 5.3 Measurement Errors Due to Improper Focus**

<table>
<thead>
<tr>
<th>Image</th>
<th>Absolute Measurement Error</th>
<th>Relative Measurement Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>–25 nm</td>
<td>–0.42%</td>
</tr>
<tr>
<td>b</td>
<td>–11 nm</td>
<td>–0.18%</td>
</tr>
<tr>
<td>c</td>
<td>0 nm</td>
<td>0</td>
</tr>
<tr>
<td>d</td>
<td>–2 nm</td>
<td>–0.03%</td>
</tr>
<tr>
<td>e</td>
<td>–3 nm</td>
<td>–0.06%</td>
</tr>
</tbody>
</table>
Resolution, repeatability, hysteresis, and drift tests were performed on both single-stage and dual-stage nanopositioners to characterize the accuracy of the devices. The details of the tests and the results are given in this chapter. The single-stage nanopositioners demonstrate the accuracy that is feasible with thermal actuators and establish a limit for the accuracy of the dual-stage nanopositioners. The experimental results are tabulated and compared to the characteristics of the micro- and nanopositioners that were reviewed in Chapter 2. A possible application of the dual-stage nanopositioners is explained and demonstrated.

6.1 Single-stage Nanopositioners

The TIM is a single-stage positioning device. Figure 6.1 is a schematic drawing of a single expansion beam that defines the design parameters of the TIM. The beam length \( L \) and angle \( \theta \) control the balance between the maximum displacement range and the stiffness of a TIM. The beam width \( w \) balances stiffness and stress. By modifying these parameters, the TIM may be adapted to specific design requirements. Decreasing the beam length
and increasing the angle both tend to reduce the range and augment the stiffness of the TIM. Greater stiffness leads to better repeatability because the TIM is better able to overcome the disturbance forces that cause random position error. The TIM is sufficiently stiff that its resolution is usually less than the smallest increment by which the current source is able to increment the position of the TIM. This increment is the product of the resolution of the current source and the sensitivity of the displacement of the TIM to the input current. Therefore, efforts to improve the resolution of the TIM should be focused on these two factors. Assuming the best available current source has been selected, the resolution observed in a test depends primarily on the sensitivity of displacement to current. There are two ways to reduce the displacement-to-current sensitivity and thus improve the resolution of the TIM: (1) reduce the range and (2) increase the operating current. A TIM with a shorter range is less sensitive to the input current and, therefore, has better resolution. Increasing the number of expansion beams improves the resolution by increasing both the operating current and the stiffness of the TIM without changing its range.

Three configurations of the TIM were tested to demonstrate the feasibility of using thermal actuators for nanopositioning and to determine the loss of accuracy that results from the addition of a second stage. Figure 6.2 contains scanning electron micrographs of
the TIM configurations. Each TIM had a stationary object near the end of the shuttle that served as a reference for position measurements. The guide on the shuttle of each TIM was intended to limit out-of-plane deflection if it occurred, but it was not expected to contact the shuttle in normal operation.

Table 6.1 summarizes the design parameters of the three TIM configurations. The TIM PRBM with $T_u = 495 \, ^\circC$ predicts ranges of 6.3 $\mu$m, 2.1 $\mu$m, and 6.2 $\mu$m for Config-

Figure 6.2  Scanning electron micrographs of the three TIM configurations that were tested
urations A, B, and C, respectively. Configuration A has shorter beams but a smaller angle than Configuration C, so they have comparable ranges. Configuration B has the largest beam angle, so it has the shortest range. Configuration A measures 396 \( \mu \text{m} \times 424 \mu \text{m} \); the footprint of Configuration B is 367 \( \mu \text{m} \times 518 \mu \text{m} \); the footprint of Configuration C is 341 \( \mu \text{m} \times 524 \mu \text{m} \).

The TIMs were operated with open loop control. The resolution of the power supply was 100 \( \mu \text{A} \) and the repeatability was \( \pm 6 \mu \text{A} \). TIM Configurations A and B were tested in a JEOL JSM-6100 SEM [118]; Configuration C was tested in an FEI XL 30 ESEM FEG [119]. Table 6.2 lists the SEM settings for all three TIM configurations.

6.1.1 TIM Configuration A

The repeatability of Configuration A was determined from 33 repetitions. The input current was 4.0 mA. The corresponding voltage was 0.56 V, which meant that the device used

<table>
<thead>
<tr>
<th>TABLE 6.1 TIM Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Parameter</strong></td>
</tr>
<tr>
<td>Number of beams</td>
</tr>
<tr>
<td>Length (L)</td>
</tr>
<tr>
<td>Angle (( \theta ))</td>
</tr>
<tr>
<td>Width (w)</td>
</tr>
<tr>
<td>Thickness (t)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 6.2 SEM Settings for Tests of Single-stage Nanopositioners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration</strong></td>
</tr>
<tr>
<td>Accelerating potential</td>
</tr>
<tr>
<td>Working distance</td>
</tr>
<tr>
<td>Magnification</td>
</tr>
</tbody>
</table>
2.2 mW of power. Figure 6.3 is a histogram of the displacement measurements. The mean and standard deviation of the position data were 221 nm and 8.4 nm, respectively. The 95% precision interval was 221 ±17 nm.

Electrical charging in the silicon contributed significantly to the variance of the data in this test. The silicon nitride layer inhibited the electron beam current as it returned to ground. The charging problem was resolved in later tests by (1) creating a conductive background with the base layer of polysilicon and grounding it to the SEM stage and (2) accelerating the electron beam with a lower voltage.

6.1.2 TIM Configuration B

The repeatability of Configuration B was measured with 31 repetitions at 10.0 mA. The voltage was 1.68 V, and the power was 16.8 mW. The brightness and contrast of the images in this test were adjusted to facilitate the selection of benchmarks during the measurement process. Configuration B moved an average of 699 nm with a standard deviation
of 5.9 nm. The distribution of the position data is represented in Figure 6.4. The precision interval was $699 \pm 12$ nm. The repeatabilities of TIM Configurations A and B have been published [85]. The values presented here differ slightly from the published results because a different method was used to identify the moving and reference objects within the images.

A hysteresis test was done with Configuration B. Its range was 2.803 µm at 14.0 mA, 3.57 V, and 50.0 mW. The hysteresis was 165 nm, or 5.9% of the full range (Figure 6.5).

### 6.1.3 TIM Configuration C

TIM Configuration C was operated in parallel with a resistor to divide the current from the power supply by a factor of 2.2. The primary purpose for the current divider circuit was to reduce the resolution of the current so that the TIM would demonstrate better resolution. For consistency, the current divider was used in all the tests of TIM Configuration C.

![Figure 6.4](image.png)  
**Figure 6.4** Histogram of the repeatability test for TIM Configuration B
The resolution test of Configuration C began at a displacement of 4.095 µm. The electrical inputs are listed in Table 6.3 and the displacements are plotted in Figure 6.6. The solid lines in Figure 6.6 are the mean displacements and the dashed lines are the precision

**TABLE 6.3** Electrical Inputs for the Resolution Test of TIM Configuration C

<table>
<thead>
<tr>
<th>Step</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.301</td>
<td>2.442</td>
<td>27.60</td>
</tr>
<tr>
<td>2</td>
<td>11.307</td>
<td>2.458</td>
<td>27.79</td>
</tr>
<tr>
<td>3</td>
<td>11.320</td>
<td>2.470</td>
<td>27.96</td>
</tr>
<tr>
<td>4</td>
<td>11.340</td>
<td>2.487</td>
<td>28.20</td>
</tr>
<tr>
<td>5</td>
<td>11.349</td>
<td>2.498</td>
<td>28.35</td>
</tr>
<tr>
<td>6</td>
<td>11.380</td>
<td>2.524</td>
<td>28.72</td>
</tr>
<tr>
<td>7</td>
<td>11.334</td>
<td>2.500</td>
<td>28.34</td>
</tr>
<tr>
<td>8</td>
<td>11.320</td>
<td>2.491</td>
<td>28.20</td>
</tr>
<tr>
<td>9</td>
<td>11.290</td>
<td>2.477</td>
<td>27.97</td>
</tr>
<tr>
<td>10</td>
<td>11.260</td>
<td>2.466</td>
<td>27.77</td>
</tr>
<tr>
<td>11</td>
<td>11.230</td>
<td>2.455</td>
<td>27.57</td>
</tr>
</tbody>
</table>
intervals at each of the steps. The resolution of the current was approximately 20 µA. All of the steps were clearly resolved. The size of step 6 was twice that of the other steps because the current was increased by twice the minimum increment from step 5 to step 6 and decreased by the same amount from step 6 to step 7. The resolution was computed from the sizes of steps 2–5 and 8–11 to be 38 nm.

The repeatability test included 20 measurements. The brightness and contrast of the images in this test were adjusted. The distribution of the displacement is plotted in Figure 6.7. The average electrical inputs were 11.25 mA, 2.460 V, and 27.68 mW. The precision interval was 4.122 µm ±14 nm.

Two hysteresis tests were performed with the same current increment (1.18 mA). Configuration C required 11.82 mA and 3.073 V, or 36.3 mW, to reach the maximum displacement of 6.150 µm. The displacement–current relation is plotted in Figure 6.8. The
hysteresis was 63 nm, or 1.03%, in the first test and 39 nm, or 0.63%, in the second test. The hysteresis in the electrical power was 0.14% of the maximum power in the first test and 0.05% in the second test.

Figure 6.7  Histogram of the repeatability test for TIM Configuration C

Figure 6.8  Results of the hysteresis test for TIM Configuration C
The drift test began at 11.94 mA and 3.054 V. The results are plotted in Figure 6.9. The displacement was initially 6.146 µm; it decreased by 1.6 nm over 100 minutes. There was not a clear trend in the data. The uncertainty of the measurement process (±6.1 nm) is larger than the average drift (−3 nm), so the drift is negligible.

6.1.4 Summary

The tests performed on single-stage nanopositioners are summarized in Table 6.4. The displacement, current, and voltage listed with each test are measured data that represent the test conditions; they are the average values for the first step of the resolution test, the average values for the repeatability tests, the maximum values for the hysteresis tests, and the initial values in the drift test. The results indicate that the TIM is suitable for nanoposition-
ing applications. The dual-stage nanopositioners driven by TIMs are expected to have greater position errors because of their complexity.

### 6.2 Dual-stage Nanopositioners

The coarse- and fine-motion stages of the nanopositioners were all tested in air to demonstrate functionality and to determine the range and electrical requirements. Displacements were measured from images acquired with an optical microscope. The optical microscope was a convenient tool for the preliminary tests because it admitted probes. The probes were useful for making electrical connections, removing debris, and manually actuating the mechanisms. The tests to characterize the accuracy of the fine motion stages were carried out in the ESEM [119] under high vacuum.

#### 6.2.1 NanoTran 1

The first stage of NanoTran 1 failed to move between its two positions. The ATIMs were not able to flip the bistable mechanisms in either direction. The safe operating limit was 380 mA and 11 V. The first stage was fragile; it was easily damaged by the probes in the

<table>
<thead>
<tr>
<th>TIM Configuration</th>
<th>Test Type</th>
<th>Result</th>
<th>Displacement</th>
<th>Current</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Repeatability</td>
<td>±17 nm</td>
<td>221 nm</td>
<td>4.0 mA</td>
<td>0.56 V</td>
</tr>
<tr>
<td>B</td>
<td>Repeatability</td>
<td>±12 nm</td>
<td>699 nm</td>
<td>10.0 mA</td>
<td>1.68 V</td>
</tr>
<tr>
<td></td>
<td>Hysteresis</td>
<td>165 nm or 5.9%</td>
<td>2.8 µm</td>
<td>14.0 mA</td>
<td>3.57 V</td>
</tr>
<tr>
<td>C</td>
<td>Resolution</td>
<td>38 nm</td>
<td>4.1 µm</td>
<td>11.30 mA</td>
<td>2.442 V</td>
</tr>
<tr>
<td></td>
<td>Repeatability</td>
<td>±14 nm</td>
<td>4.1 µm</td>
<td>11.25 mA</td>
<td>2.460 V</td>
</tr>
<tr>
<td></td>
<td>Hysteresis</td>
<td>39 nm or 0.63%</td>
<td>6.1 µm</td>
<td>11.82 mA</td>
<td>3.073 V</td>
</tr>
<tr>
<td></td>
<td>Drift</td>
<td>≤2 nm over 100 min.</td>
<td>6.1 µm</td>
<td>11.94 mA</td>
<td>3.054 V</td>
</tr>
</tbody>
</table>
attempt to move it to the second position. The electrical contacts did not conduct. The gold-coated beams of the bistable mechanisms transmitted sufficient current to operate the second stage. The resistance of a single bistable mechanism without gold was 890 Ω; the gold layer reduced the resistance to 25 Ω. The second stage did not function in the SEM, but it was observed in the optical microscope to reach a displacement of 3.8 µm with 28.0 mA and 13.56 V (380 mW).

6.2.2 NanoTran 2

NanoTran 2 was not able to complete the coarse motion. The forward actuator could be safely operated up to 180 mA and 11 V. It moved the first stage but did not pass the unstable equilibrium position. The reverse actuator succeeded once with a current of 240 mA, but the ATIMs melted. The compact TIM between the beams of the bistable mechanisms was not as stiff as a simple shuttle. The bistable mechanisms did not perform properly because of the relaxed constraint, although they were stable in the second position. The compact TIM had a limited range of motion. The expansion beams elongated enough to close the gaps and contact the anchored guide blocks, but the shuttle only moved 0.9 µm at 30.1 mA and 12.3 V (370 mW).

6.2.3 NanoTran 3

The first stage of NanoTran 3 performed reliably. It required 159 mA at 7.6 V, or 1.21 W, to move from the first position to the second and 141 mA at 6.6 V, or 0.93 W, to return to the first position. The range of the first stage was 52.1 µm. The second stage traveled an
additional 8.6 µm in vacuum, extending the total range to 60.7 µm. The second stage reached a displacement of 10.4 µm in air with 70.0 mA and 5.88 V (412 mW).

The resolution, repeatability, hysteresis, and drift of the second stage were determined experimentally. Table 6.5 lists the SEM settings for all of the tests. The results of these tests are presented and discussed in the following sections.

6.2.3.1 Resolution

Two tests were performed to measure the resolution of the second stage; both began at a displacement greater than half of the range. In the first resolution test, the nominal current increment was 0.1 mA. The measured values of the current, voltage, and power for each step are listed in Table 6.6. Figure 6.10a shows the results; the mean displacement for each step is marked with a solid line, and the precision interval is delimited with dashed lines.

<table>
<thead>
<tr>
<th>TABLE 6.5 SEM Settings for Tests of Dual-stage Nanopositioners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Tests</strong></td>
</tr>
<tr>
<td>Accelerating potential</td>
</tr>
<tr>
<td>Working distance</td>
</tr>
<tr>
<td>Magnification</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 6.6 Electrical Inputs for the First Resolution Test on NanoTran 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
Figure 6.10 Results of the resolution tests performed on NanoTran 3 with nominal current increments of (a) 0.1 mA and (b) 0.2 mA
The nanopositioner was not able to resolve steps of this size. It did not always move when the input changed, and the step sizes were not consistent.

The nominal current increment in the second resolution test was 0.2 mA. The electrical inputs are summarized in Table 6.7 and the measurements are plotted in Figure 6.10b. The nanopositioner exhibited stick–slip behavior at step 3, indicating that the second stage contacted the substrate. The abrupt movement after the third measurement increased the width of the precision interval. The displacement at step 4 was slightly less than the displacement in the last seven measurements at step 3; the nanopositioner did move in reverse, but it did not move beyond the precision interval of step 3, so step 4 was not resolved. The nanopositioner clearly resolved steps 2, 3, and 5, with respect to the steps immediately preceding them. The sizes of these steps were 142 nm, 236 nm, and 132 nm, respectively. The resolution of the nanopositioner was 170 nm.

6.2.3.2 Repeatability

The first repeatability test was performed before the problem of electrical charge accumulation on the die was completely resolved. The objects in the SEM images drifted during the test; the microscope stage had to be moved to keep the objects in view. Image drift is a common result of charge accumulation. Ten measurements were taken. The input current

<table>
<thead>
<tr>
<th>Step</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.58</td>
<td>2.501</td>
<td>73.98</td>
</tr>
<tr>
<td>2</td>
<td>29.75</td>
<td>2.518</td>
<td>74.91</td>
</tr>
<tr>
<td>3</td>
<td>29.95</td>
<td>2.539</td>
<td>76.04</td>
</tr>
<tr>
<td>4</td>
<td>29.75</td>
<td>2.518</td>
<td>74.91</td>
</tr>
<tr>
<td>5</td>
<td>29.58</td>
<td>2.500</td>
<td>73.95</td>
</tr>
</tbody>
</table>
was 30.0 mA; the average voltage was 2.345 V; the nanopositioner used 70.4 mW of power. The displacements are plotted on a histogram in Figure 6.11a. The mean displacement was 5.300 µm, and the repeatability was ±99 nm.

There were 29 measurements taken in the second repeatability test. The current was cycled from 0 mA to 29.58 mA for each repetition. The average voltage and power were 2.501 V and 74.0 mW, respectively. Figure 6.11b presents the distribution of the displacements. The mean displacement was 4.550 µm, and the repeatability was ±124 nm.

The third repeatability test consisted of 31 measurements. Unlike the second repeatability test, the nanopositioner was not turned off before each repetition. The current was cycled between 17.71 mA and 26.61 mA, so the TIMs did not lose contact with the sliding frame of the first stage. The mean displacements at the low and high current levels were 0.603 µm and 3.691 µm, respectively; the net displacement was 3.088 µm. The average voltage was 2.186 V and the power was 58.2 mW at the high current level. The distribution of the displacement at the high current level is shown in Figure 6.11c. By eliminating the random error associated with gripping and releasing the first stage, the repeatability was improved to ±37 nm.

6.2.3.3 Hysteresis

Two hysteresis tests were performed. In the first test, the current was stepped from 0 mA to 33.5 mA and back to 0 mA in increments of 3.35 mA. The displacements measured at each step are plotted in Figure 6.12. The nanopositioner required about 16 mA to close the gaps between the TIMs and the first stage. After making contact, the TIMs compressed the amplifying mechanism, and the second stage moved. The maximum displacement was
Figure 6.11  Histograms for the (a) first, (b) second, and (c) third repeatability tests performed on NanoTran 3
8.534 µm and required 2.919 V and 97.8 mW. The largest hysteresis was 560 nm, or 6.6% of the full range. The displacements measured when the device was moving in the reverse direction were all greater than the forward measurements made at the same steps. Coulomb friction opposes motion, so it is probably the cause of the hysteresis. The electrical data present additional evidence to support this conclusion. The electrical power is proportional to the resistance, which changes with temperature. The hysteresis in the power was 0.09% of the maximum, and the rate of heat transfer must equal the electrical power at steady state, so the temperature of the device at each current was nearly equal for the forward and reverse portions of the test. The equilibrium position is unique for each temperature; therefore, a mechanical force displaced the second stage from its equilibrium position.

Figure 6.12 Results of the hysteresis tests performed on NanoTran 3
In the second test, the current began at 15.78 mA and increased by increments of 1.77 mA up to 33.5 mA; then it decreased by the same increments back to 15.78 mA. The gaps were closed on the first step, so the other steps all had positive displacements (Figure 6.12). The nanopositioner achieved a maximum displacement of 8.643 μm with 2.918 V and 97.8 mW of power. The hysteresis was 477 nm, or 5.5% of the full range. The hysteresis in the power was 0.08%.

6.2.3.4 Drift

Position errors are expected to be greatest when the displacement is large, so the error measured near the displacement limit may be assumed to be an upper bound for the entire range of motion. The drift was expected to be small, so the test was performed near the limit of the range, at a displacement of 6.965 μm. The measured current was 32.50 mA, and the voltage was 2.800 V. Time zero corresponded to the beginning of the first SEM scan. The first five measurements were taken at intervals of 75 s. Subsequent measurements were taken at 10 minutes from the first image and every 10 minutes thereafter, up to a total time of 60 minutes. The drift is plotted against time in Figure 6.13. The second stage drifted 25 nm over the course of the test. Substrate heating was probably the cause of the drift observed in this test. The trend matches the transient response of a first-order dynamic system, as would be expected with thermal drift. By fitting a negative exponential curve to the data, the time constant was estimated to be about 6 minutes. The fact that the displacement increased over time is consistent with the explanation of thermal drift given in Section 5.1.1.2.
Table 6.8 summarizes the experimental results for the second stage of NanoTran 3. As with Table 6.4, the displacement, current, and voltage listed with each test are the average values for the first steps of the resolution tests, the average values for the repeatability tests, the maximum values for the hysteresis tests, and the initial values in the drift test.

**Figure 6.13** Drift of NanoTran 3

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Test Number</th>
<th>Result</th>
<th>Displacement</th>
<th>Current</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1</td>
<td>—</td>
<td>4.5 µm</td>
<td>29.58 mA</td>
<td>2.500 V</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>170 nm</td>
<td>4.6 µm</td>
<td>29.58 mA</td>
<td>2.501 V</td>
</tr>
<tr>
<td>Repeatability</td>
<td>1</td>
<td>±99 nm</td>
<td>5.3 µm</td>
<td>30.0 mA</td>
<td>2.345 V</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>±124 nm</td>
<td>4.6 µm</td>
<td>29.58 mA</td>
<td>2.501 V</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>±37 nm</td>
<td>3.7 µm</td>
<td>26.61 mA</td>
<td>2.186 V</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>1</td>
<td>560 nm or 6.6%</td>
<td>8.5 µm</td>
<td>33.5 mA</td>
<td>2.919 V</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>477 nm or 5.5%</td>
<td>8.6 µm</td>
<td>33.5 mA</td>
<td>2.918 V</td>
</tr>
<tr>
<td>Drift</td>
<td>1</td>
<td>25 nm over 60 min.</td>
<td>7.0 µm</td>
<td>32.50 mA</td>
<td>2.800 V</td>
</tr>
</tbody>
</table>
6.2.4 NanoTran 4

NanoTran 4 demonstrated successful coarse and fine positioning in multiple tests. The range of the coarse motion was 56.2 µm, which is 2% less than the predicted range. The forward motion required 160 mA and 7.6 V (1.22 W); the reverse motion required 185 mA and 10.8 V (2.00 W). Heating the bistable mechanism with 5.51 mA and 10.0 V (55.1 mW) resulted in a displacement of 1.4 µm. The fine motion range was 5.0 µm in vacuum. The total range of NanoTran 4 was 61.2 µm.

The fine motion of NanoTran 4 was characterized in the ESEM [119]. The SEM settings are listed in Table 6.5. NanoTran 4 operated at low current (less than 2.2 mA), which was far below the limit of the power supply (1 A). The resolution of the current, 0.1 mA, was 5% of the operating current, so the number of possible current settings was quite limited. This restricted the selection of the current increments for the resolution and hysteresis tests.

6.2.4.1 Resolution

Two resolution tests were conducted with a current increment of 0.1 mA. The first test began at 1.80 mA (Table 6.9) and an average displacement of 2.205 µm. The displace-

<table>
<thead>
<tr>
<th>Step</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.80</td>
<td>3.53</td>
<td>6.35</td>
</tr>
<tr>
<td>2</td>
<td>1.87</td>
<td>3.77</td>
<td>7.06</td>
</tr>
<tr>
<td>3</td>
<td>1.97</td>
<td>4.23</td>
<td>8.33</td>
</tr>
<tr>
<td>4</td>
<td>1.87</td>
<td>3.87</td>
<td>7.24</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>3.57</td>
<td>6.43</td>
</tr>
</tbody>
</table>
ments are plotted in Figure 6.14a. NanoTran 4 resolved all of the steps; the resolution was 571 nm. The maximum hysteresis observed in this test was 586 nm.

The second resolution test began at a lower current and a displacement of 1.804 µm (Table 6.10). The test consisted of three ascending steps. Figure 6.14b shows the results. The displacement that occurred during the measurements at step 2 enlarged the precision interval such that the third step was not resolved. A resolution of 939 nm was measured in this test. The narrow precision intervals in the first test suggest that smaller resolution might be achieved if the resolution of the current were reduced. However, the second test showed that friction would probably cause the resolution to be at least 500 nm.

6.2.4.2 Repeatability

The first repeatability test included 27 measurements. The average current, voltage, and power were 2.00 mA, 4.35 V, and 8.70 mW, respectively. Figure 6.15a is a histogram of the displacement measurements. The mean is 3.565 µm. The last five repetitions yielded displacements substantially below the other 22 measurements and formed a second mode in the distribution. The repeatability was ±71 nm.

The second measurement of the repeatability was made with 30 repetitions at an average current of 1.75 mA. The average voltage was 3.45 V, and the power was 6.03 mW. The histogram in Figure 6.15b shows that three repetitions had significantly greater displacements than the other 27; these repetitions were scattered throughout the test, indicating the presence of a random disturbance force. The precision interval was 2.364 µm ±126 nm.
Figure 6.14 Results of the (a) first and (b) second resolution tests performed on NanoTran 4
TABLE 6.10  Electrical Inputs for the Second Resolution Test on NanoTran 4

<table>
<thead>
<tr>
<th>Step</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.65</td>
<td>3.15</td>
<td>5.18</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>3.57</td>
<td>6.24</td>
</tr>
<tr>
<td>3</td>
<td>1.82</td>
<td>3.88</td>
<td>7.06</td>
</tr>
</tbody>
</table>

\[ \text{(a) Histograms for the (a) first and (b) second repeatability tests performed on NanoTran 4} \]
6.2.4.3 Hysteresis

A hysteresis test was conducted between currents of 0.48 mA and 2.16 mA with an increment of 0.19 mA. Figure 6.16 is the displacement–current relation. NanoTran 4 reached a displacement of 5.047 µm with 5.45 V and 11.8 mW. The hysteresis was 1.110 µm, or 22% of the full range. The hysteresis in the power was 6.8%.

6.2.4.4 Drift

The drift of NanoTran 4 was measured for 40 minutes from an initial displacement of 1.875 µm. The current was 1.92 mA and the voltage was 3.77 V at the beginning of the test. The drift is plotted in Figure 6.17. It follows a negative exponential trend with a time constant of 10 minutes. The maximum drift was 1.629 µm, resulting in a final displacement of 3.504 µm.
The tests performed on NanoTran 4 are summarized in Table 6.11. The displacement, current, and voltage columns have the same meanings as in Table 6.8. Low stiffness made NanoTran 4 susceptible to disturbances caused by friction.

**Figure 6.17** Drift of NanoTran 4

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Test Number</th>
<th>Result</th>
<th>Displacement</th>
<th>Current</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1</td>
<td>571 nm</td>
<td>2.2 µm</td>
<td>1.80 mA</td>
<td>3.53 V</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>939 nm</td>
<td>1.8 µm</td>
<td>1.65 mA</td>
<td>3.15 V</td>
</tr>
<tr>
<td>Repeatability</td>
<td>1</td>
<td>±71 nm</td>
<td>3.6 µm</td>
<td>2.00 mA</td>
<td>4.35 V</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>±126 nm</td>
<td>2.4 µm</td>
<td>1.75 mA</td>
<td>3.45 V</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>1</td>
<td>1.110 µm or 22%</td>
<td>5.0 µm</td>
<td>2.16 mA</td>
<td>5.45 V</td>
</tr>
<tr>
<td>Drift</td>
<td>1</td>
<td>1.629 µm over 40 min.</td>
<td>1.9 µm</td>
<td>1.92 mA</td>
<td>3.77 V</td>
</tr>
</tbody>
</table>
6.2.5 Rotational Nanopositioner

The first stage of the rotational nanopositioner performed the same as NanoTran 2. The second stage rotated $0.3^\circ$ ($5 \times 10^{-3}$ radians) with 29.7 mA and 5.7 V (169 mW). The rotational range is sufficient; macroscopic nanopositioners with rotational degrees of freedom have ranges of about $0.21^\circ$ ($3.6 \times 10^{-3}$ radians) [35,58,52,62,31]. The accuracy of the rotating stage was not characterized.

6.3 Comparisons

In this chapter, four performance characteristics were measured for a set of single-stage and dual-stage nanopositioners; these are summarized in Table 6.12. The TIMs demonstrated superior accuracy in comparison with NanoTran 3 and NanoTran 4. The repeatability of NanoTran 3 is double that of TIM Configuration C, and its resolution is four times larger. Hysteresis is an order of magnitude greater for NanoTran 3 than for TIM Configuration C. NanoTran 3 exhibits measurable drift, but the TIM does not. Position errors are approximately twice as large with NanoTran 4 as with NanoTran 3. The drift of NanoTran 4 is two orders of magnitude greater than that of NanoTran 3.

<table>
<thead>
<tr>
<th>Device</th>
<th>Resolution</th>
<th>Repeatability</th>
<th>Hysteresis</th>
<th>Drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM Configuration A</td>
<td>—</td>
<td>±17 nm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>TIM Configuration B</td>
<td>—</td>
<td>±12 nm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>TIM Configuration C</td>
<td>38 nm</td>
<td>±14 nm</td>
<td>39 nm or 0.6%</td>
<td>~2 nm over 100 min.</td>
</tr>
<tr>
<td>NanoTran 3</td>
<td>170 nm</td>
<td>±37 nm</td>
<td>477 nm or 5.5%</td>
<td>25 nm over 60 min.</td>
</tr>
<tr>
<td>NanoTran 4</td>
<td>571 nm</td>
<td>±71 nm</td>
<td>1.1 µm or 22%</td>
<td>1.6 µm over 40 min.</td>
</tr>
</tbody>
</table>
The complexity of the dual-stage designs introduces many sources of position error that do not affect the TIMs. The translating stages tend to contact the substrate because the lengths of the compliant beams that attach them to the anchors are much greater than the out-of-plane thickness. The TIMs are stiffer because they are anchored directly to the substrate. The TIMs set a lower limit for the position error of the dual-stage nanopositioners.

Table 6.13 presents the characteristics of the single-stage and dual-stage nanopositioners in the same format as Tables 2.1–2.7. The force, natural frequency, and bandwidth are not tabulated because they were not measured for any of these devices. The nanopositioners do not have sensors or feedback control systems at present.

The TIMs that were tested in this research are similar to the thermal positioning devices in Table 2.5. The resolution and repeatabilities of the TIMs, which are listed in the resolution column of Table 6.13, are comparable to those of electrostatic nanopositioners (Table 2.1). The TIMs have smaller footprints than some electrostatic devices with the same range of motion [17–19,21,36].

<table>
<thead>
<tr>
<th>Device</th>
<th>Degrees of Freedom</th>
<th>Range (µm)</th>
<th>Resolution (nm)</th>
<th>Range-to-Resolution Ratio</th>
<th>Footprint (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM Configuration A</td>
<td>1</td>
<td>6.3</td>
<td>17</td>
<td>370</td>
<td>168×10⁻³</td>
</tr>
<tr>
<td>TIM Configuration B</td>
<td>1</td>
<td>2.8</td>
<td>12</td>
<td>230</td>
<td>190×10⁻³</td>
</tr>
<tr>
<td>TIM Configuration C</td>
<td>1</td>
<td>6.1</td>
<td>38</td>
<td>161</td>
<td>179×10⁻³</td>
</tr>
<tr>
<td>NanoTran 3</td>
<td>1st Stage: 1</td>
<td></td>
<td>52.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd Stage: 1</td>
<td>8.6</td>
<td>170</td>
<td>357</td>
<td>5.60</td>
</tr>
<tr>
<td>NanoTran 4</td>
<td>Coarse Motion: 1</td>
<td></td>
<td>56.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine Motion: 1</td>
<td>5.0</td>
<td>571</td>
<td>107</td>
<td>5.32</td>
</tr>
</tbody>
</table>

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NanoTran 3 and NanoTran 4 have larger ranges and footprints than most of the thermal positioning devices but are similar to the electrostatic positioning devices in terms of range and size. Many of the piezoelectric and magnetic devices have both greater range and smaller resolution than NanoTran 3 and NanoTran 4; their range-to-resolutions are an order of magnitude higher.

The integration of two stages on a silicon chip is novel. The first stages of most dual-stage nanopositioners are macroscopic machines, but NanoTran 3 is entirely fabricated on the micro scale. Accordingly, the range and footprint of NanoTran 3 are smaller than those of the dual-stage, piezoelectric nanopositioners [39,40,42]. NanoTran 3 has potential for increased range and improved accuracy that may eventually make it superior to single-stage nanopositioners. The design must be improved to eliminate sources of friction. Mass production may be feasible because NanoTran 3 is surface micromachined. If so, the reduced cost could make the dual-stage nanopositioner a competitive option for commercial applications.

6.4 Optical Modulator Application

A beam of light that strikes a grating is diffracted into multiple beams at various angles (Figure 6.18). The diffracted beam of order zero is the direct reflection (or transmission) of the incident beam. The other diffracted beams (termed orders) are numbered sequentially in either direction from the zero order. The intensities of the diffracted orders decrease with increasing angle; higher orders receive a smaller fraction of the incident light. Light interacts with two gratings of equal period in the same manner, but the relative intensities of the diffracted orders vary as a function of the phase difference between the
gratings. The functional dependence is not derived here, but it is measured. Sene et al. modulated the intensity of a laser by shifting a pair of surface-micromachined gratings [9]. The gratings were fabricated in the two releasable layers of the MUMPs process and had a period of 8 µm.

Diffraction gratings were fabricated with the nanopositioners to demonstrate the possibility of using them as optical modulators (Figure 6.19). One grating was etched in the base layer of polysilicon; a second grating was formed next to it in the second releasable layer (Figure 6.20). The two gratings were designed with a period of 6 µm. Compensation was included in the designs for the etch bias that causes narrow beams to be fabricated at less than the design width; as a result, the beams and slits had nearly equal widths. The coarse motion places the second grating directly above the first. The fine
motion shifts the upper grating with respect to the lower grating in the direction perpendicular to the slits and has a range of about one grating period. The phase of the upper grating relative to the lower grating is the fraction of the grating period by which the slits are offset (Figure 6.21).

**Figure 6.19** Diffraction grating on NanoTran 4

**Figure 6.20** Portions of (a) the diffraction grating in the base layer of polysilicon and (b) the grating attached to the second stage of NanoTran 3
The gratings were tested with a red laser of wavelength $\lambda = 633$ nm and an infrared (IR) laser of wavelength $\lambda = 1300$ nm; diffraction patterns were observed with both lasers. Red light reflects off of silicon, but infrared radiation is transmitted (Figure 6.18). The back side of the MEMS chip was polished to improve the clarity of the IR diffraction pattern. The chip was mounted on a fiberglass wafer board with holes at the locations where the IR laser would pass through. The diffracted orders of the IR laser were difficult to locate because of their low intensity; predictions of the diffraction angles made it possible to place a detector at locations where the orders could be measured. The diffraction angle analysis follows.

The incident and diffracted beams are illustrated in Figure 6.22. The incident beam angle is $\theta_i$, the diffracted beam angle is $\theta_d$, and the grating period is $\Lambda$. The incident wave vector is

$$K_i = \frac{2\pi}{\lambda}$$  \hspace{1cm} (6.1)$$

and its $x$ component is

$$K_{ix} = \frac{2\pi}{\lambda} \sin \theta_i$$  \hspace{1cm} (6.2)$$

The wave vector of the grating is
The wave vector of a diffracted order, $K_d$, has the same magnitude as the incident wave vector:

$$K = \frac{2\pi}{\lambda}$$  \hspace{1cm} (6.3)

The wave vector of a diffracted order, $K_d$, has the same magnitude as the incident wave vector:

$$K_d = \frac{2\pi}{\lambda}$$  \hspace{1cm} (6.4)

The $x$ component of $K_d$ is

$$K_{dx} = K_{ix} + mK = \frac{2\pi}{\lambda} \sin\theta_d$$  \hspace{1cm} (6.5)

The integer $m$ is the order number. Solving Equation 6.5 for the diffraction angle yields

$$\theta_d = \sin^{-1}\left(m\frac{\lambda}{\Lambda} + \sin\theta_i\right)$$  \hspace{1cm} (6.6)

The angle of incidence was $0^\circ$ for both the red and IR lasers. The predicted diffraction angles are plotted in Figure 6.18 and listed in Table 6.14 along with measured values. The IR laser developed a larger spread in the diffracted orders and was expected to more
clearly illustrate the function of the double grating; therefore, modulation tests were only performed with the IR laser.

Aligning the grating with the red laser was simple because the incident spot was visible on the surface of the chip. In order to align the infrared laser with the grating, it was combined with the red laser through a polarizing beam splitter. Figure 6.23 shows the experimental setup. The lasers entered the splitter from orthogonal directions. The laser emitters were oriented such that the IR laser was mostly transmitted and the red laser was mostly reflected. The two lasers were collinear as they emerged from the beam splitter; therefore, aligning the grating with the red laser simultaneously aligned it with the IR laser.

<table>
<thead>
<tr>
<th>Order</th>
<th>Red Light Predicted</th>
<th>Measured</th>
<th>Infrared Light Predicted</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6°</td>
<td>6°</td>
<td>13°</td>
<td>13°</td>
</tr>
<tr>
<td>2</td>
<td>12°</td>
<td>11°</td>
<td>26°</td>
<td>24°</td>
</tr>
<tr>
<td>3</td>
<td>18°</td>
<td>17°</td>
<td>41°</td>
<td>43°</td>
</tr>
<tr>
<td>4</td>
<td>25°</td>
<td>23°</td>
<td>60°</td>
<td>70°</td>
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<td>32°</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>39°</td>
<td>34°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.23** Setup for optical modulation experiments
The power of the IR laser drifted over time. The zero-order power was monitored for 120 s prior to the tests. The total drift was less than 0.7%. The power radiated by the thermal actuators was measured to verify that it would not interfere with the experiments. The actuators emitted negligible power over their full range of motion.

The relationship between the phase difference of a pair of gratings and the power of the diffracted orders was determined experimentally. Gratings on two copies of NanoTran 3 (labeled NanoTran 3A and NanoTran 3B) were tested. The first step was to obtain the displacement–current relations for each of the nanopositioners in air. Experiments were conducted in an optical microscope, and the plots in Figure 6.24 were created. The position of the moving grating was determined by evaluating curve fits to the displacement–current relations.

The input current and the power of orders zero and one were measured as the second stages of the nanopositioners moved through their full range. The power distributed to orders zero and one is plotted against the phase difference of the gratings in Figures 6.25 and 6.26. The power is normalized by the power measured at the beginning of each test (Table 6.15). The power of order zero increases and the power of order one decreases with increasing phase difference, indicating an exchange of power. Drift of the laser power does affect the results, but it is not sufficient to account for the observed trends. The power of the zero order peaks at phase differences of 180° and 540°, indicating periodic behavior. The first order does not appear to be periodic with the grating phase; however, the nanopositioners do modulate the laser significantly, and the results are repeatable. The modulation achieved by each of the nanopositioners is listed in Table 6.16.
The steady drift of the laser power causes systematic error in the power measurements. The power measured at each diffracted order could be normalized by the incident power to eliminate the drift. Measuring the power of the incident laser would necessarily interrupt it, but the incident power may be estimated by sampling the portion of the laser that is reflected by the beam splitter during the test. The reflected beam can be measured without disrupting the experiment because it exits the beam splitter perpendicular to the

---

**Figure 6.24** Displacement–current relations for (a) NanoTran 3A and (b) NanoTran 3B in air
transmitted beam. The reflected power is related to the transmitted power by a scalar that depends on the polarization angle. The scalar may be determined prior to the experiment by measuring both the reflected and transmitted beams.

**Figure 6.25** Optical power distributed to orders (a) zero and (b) one as a function of the phase difference of the gratings on NanoTran 3A
The laser used in the experiments had a diameter about ten times the size of the grating. The experiments might be improved by focusing the laser, such as by transmitting

**Figure 6.26** Optical power distributed to orders (a) zero and (b) one as a function of the phase difference of the gratings on NanoTran 3B
it through an optic fiber, so that it only illuminated the gratings. This would reduce the noise caused by light scattering off of objects around the grating.

The gratings might be enlarged to increase the clarity of the results. This would require the first stage of the nanopositioner to move farther, and the second stage would have to be more stiff to move the larger gratings with the accompanying increase in the friction force. It might be necessary to connect the beams of the moving grating with perpendicular beams at intervals of 250 µm in order to overcome stiction.

The dual-stage nanopositioners were shown to function as optical modulators. The first diffracted order of an IR laser \((\lambda = 1300 \text{ nm})\) was modulated by as much as \(-2.5 \text{ dB}\). The effectiveness of the optical modulators may be increased by improving the designs and the experimental procedures.

**TABLE 6.15** Initial Power Measurements

<table>
<thead>
<tr>
<th>Test</th>
<th>NanoTran 3A Order Zero</th>
<th>NanoTran 3A Order One</th>
<th>NanoTran 3B Order Zero</th>
<th>NanoTran 3B Order One</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.336 µW</td>
<td>115 nW</td>
<td>7.588 µW</td>
<td>88.20 nW</td>
</tr>
<tr>
<td>2</td>
<td>9.127 µW</td>
<td>115 nW</td>
<td>7.729 µW</td>
<td>87.86 nW</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>113 nW</td>
<td></td>
<td>87.81 nW</td>
</tr>
</tbody>
</table>

**TABLE 6.16** Modulation of the First Diffracted Order of the Infrared Laser

<table>
<thead>
<tr>
<th>Test</th>
<th>NanoTran 3A</th>
<th>NanoTran 3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–2.4 dB</td>
<td>–1.6 dB</td>
</tr>
<tr>
<td>2</td>
<td>–2.5 dB</td>
<td>–1.5 dB</td>
</tr>
<tr>
<td>3</td>
<td>–2.4 dB</td>
<td>–1.6 dB</td>
</tr>
</tbody>
</table>
CHAPTER 7 CONCLUSION

The designs presented in Chapter 3 and the experiments discussed in Chapter 6 contribute to the development of micro-scale nanopositioners. This chapter reviews the objectives of this project and its accomplishments, suggests improvements to the design of the nanopositioners, and indicates possible directions for future research work.

7.1 Contributions

This work demonstrated that a nanopositioner with two stages can be fabricated by surface micromachining and operated on a silicon chip. The hypothesis was realized with NanoTran 3, which has a coarse positioning stage that moves between two discrete positions and a fine positioning stage that moves continuously throughout its range. The entire device was fabricated in MUMPs with a footprint of 3.431 mm × 1.632 mm. Both stages were powered by thermal actuators and had one translational degree of freedom.

The dual-stage nanopositioner was intended to have a range greater than 50 µm and resolution smaller than 25 nm (Section 1.3). NanoTran 3 exceeded the desired range but did not meet the objective for resolution. The range of NanoTran 3 was 60.7 µm; the
resolution was 170 nm. The resolution was poor because the compliant amplifier mechanism that moved the second stage encountered friction that inhibited it from reaching its equilibrium displacement. A repeatability of ±37 nm was demonstrated. The hysteresis in the motion of the second stage was 477 nm or 5.5% of its range. The second stage drifted 25 nm during start-up.

The inclusion of a bistable mechanism with the first stage is ideal for applications where an object needs to be repeatedly placed in the same position. Three such applications are the wavelength-specific add–drop device, the parallel laser printer, and the optical modulator mentioned in Section 1.3. The nanopositioner successfully modulated the intensity of the first diffracted order of an infrared laser by changing the relative position of a pair of gratings (Section 6.4). Continued growth is projected for MEMS and nanopositioning technologies. As applications for micro-scale nanopositioners are developed, thermal actuators might fill a niche for small actuators with large output forces.

7.2 Recommendations

The nanopositioner designs may be modified to improve performance. A few ideas are presented here. The two principal sources of position error are friction with the substrate and gaps that the second-stage actuators must close. Specific recommendations are made for handling these sources of uncertainty. Ideas for additional tests, improvements to the position measurement process, and a three-degree-of-freedom thermal nanopositioner are considered.
7.2.1 Improvements to the Nanopositioners

The ATIMs were not able to actuate the first stages of NanoTran 1 or NanoTran 2. There were two bistable mechanisms for each ATIM in these devices. The ATIM that was incorporated into the nanopositioners was a modification of an existing design. The TIMs on either side of the amplifying mechanism were duplicated to provide more force, but the amplifying beams were not re-designed. They could be made more stiff so that they would deliver more force before buckling. Out-of-plane buckling was also a problem; another guide plate could be placed on the shuttle of each TIM to prevent it. The first stages were driven by sets of two ATIMs. More force would be available if each set contained three or four ATIMs. The power requirements would still be manageable. Four ATIMs would require approximately 360 mA at 10 V, or 3.6 W, in air. If NanoTran 1 had eight ATIMs to move the first stage in each direction it would require about 720 mA and 7.2 W.

The gratings on the second stages of the nanopositioners are large and susceptible to electrostatic attraction to the substrate. Versions of the nanopositioners might be fabricated without gratings for the purpose of testing the performance limits of the nanopositioners. Separate devices could be used to demonstrate possible applications.

Greater stiffness would make the nanopositioners less sensitive to mechanical disturbances. The stiffness of NanoTran 3 may be increased by increasing the angle of the beams in the amplifier mechanism (Figure 3.15e). This would also reduce the range of the second stage, but the trade-off would be worth making.

Controlling the second stages of the nanopositioners was the most significant challenge in this project. The control signal was transmitted through the first stage, which moved across the substrate. Two methods were proposed in Section 3.2 for controlling the
second stages. NanoTran 1 and NanoTran 2 delivered an electrical input to the second-stage TIMs by means of gold-coated bistable mechanisms. NanoTran 3 received a mechanical input from TIMs attached to the substrate. Both concepts required the second-stage actuators to close gaps. In the case of electrical input, the gaps were necessary because the sliding TIM had to be supported by blocks anchored to the substrate. The sliding TIMs were the only current path between the two sections of the first stage so that they would not be short-circuited. Polysilicon structural members could not be used to constrain the expansion of the TIMs. NanoTran 3 included gaps because the TIMs that provided the mechanical input were mounted on the substrate. The gaps might be replaced by flexible couplings. In that case, the TIMs would pull on the first stage to avoid buckling the flexures, so a different amplifier mechanism would be required.

Two possible alternatives to electrical actuation are photothermal actuation and heat transfer by a combination of conduction and radiation. Either of these techniques would permit a stiff polysilicon frame to surround the thermal actuator and provide mechanical constraint. The frame would enable the actuator to operate without contacting any anchored objects.

Photothermal actuation has been accomplished with an infrared laser [86]. A 150-µm-diameter plate was mounted on the shuttle of a chevron actuator to absorb the radiation. The actuator had a footprint of approximately 720 µm × 780 µm and a range of 1.5 µm. The laser emitted 210 mW.

The SUMMiT process has four releasable layers. The second stage might be created in the first two layers with a stiff support frame. A heating element could be fabricated in the upper layers and anchored to the substrate at the location where the second
stage would be during the fine motion. The heating element would need to be positioned such that it radiated heat to the sliding TIM and not the support frame.

In the future, surface micromachining processes might include a releasable silicon nitride layer with the capability to link mechanical components without electrically connecting them. The support frame for the sliding TIM could be fabricated of silicon nitride. Then the anchored guide blocks would not be necessary and the second stage could be electrically actuated.

7.2.2 Future Work

The first stages of the nanopositioners need to be characterized in the SEM. The actuators would require less power in vacuum than in air. Tests should be performed in vacuum to determine the minimum current and voltage required to move the first stages in each direction. The repeatability of the first stage should be measured in the SEM. The first stage needs to move to its second position precisely so that it does not inhibit the precision of the second stage.

Some additional tests could be performed to better characterize the accuracy of the nanopositioners. The sensitivity of the fine motion to changes in the substrate temperature may be determined by mounting the chip on the Peltier stage in the SEM. The Peltier stage is capable of raising and lowering the substrate temperature from room temperature by 10 °C. The nanopositioner could be driven with a constant current while the substrate temperature varied, and the position could be measured with the SEM.

Following the work of Lott [6], the substrate temperature was assumed to remain close to room temperature while the thermal actuators operated. This assumption should
be verified by placing a thermocouple under the chip and performing a drift test. It would be advisable to monitor the substrate temperature during every test.

The repeatabilities of NanoTran 3 and NanoTran 4 were measured as the nanopositioners moved in the forward direction. A test could be performed to characterize the repeatability of the reverse motion. The position would be measured with zero current and at the safe operating limit before the test. These measurements would serve as reference positions for calculating displacements. Then the current would be set to the value that resulted in a displacement equal to half the range. The current would be cycled between the mid-range current and the safe operating limit. The precision interval of the half-range position would be computed.

The nanopositioner was operated with open-loop control. Feedback control has the ability to eliminate random errors, drift, and hysteresis, leaving only the trueness of the measurement system and the resolution of the nanopositioner to determine the accuracy. Feedback control has been demonstrated with an on-chip piezoresistive sensor [10]. If implemented, feedback control could significantly improve the performance of the nanopositioner.

Many commercial software packages perform image analysis, including motion tracking. A routine could be added to the image processor that would locate the moving and reference objects in SEM images. The image processor works best if the reference object is at the same location in all the images. If it were located automatically with accuracy on the order of 10 pixels, the images could be cropped so as to include only the portions of the objects that were needed for measurement. This would eliminate image drift.
The automated method would decrease the processing time sufficiently for measurements to be made immediately upon acquisition of the images.

The one-degree-of-freedom nanopositioners are a first step toward a three-degree-of-freedom nanopositioner. Additional degrees of freedom may be added by duplicating the actuators. One method for combining multiple degrees of freedom is to stack several actuators on top of each other as separate stages (Figure 1.4b). Each degree of freedom is controlled by a single actuator. Another approach is to design a compliant mechanism that converts multiple inputs to a single output with multiple degrees of freedom (Figure 1.4a) [62]. Digital compliant mechanisms are designed to have many degrees of freedom, each controlled by a binary actuator. There is a unique equilibrium position for each combination of actuator states. A digital compliant mechanism with six actuators and 64 discrete locations has been demonstrated on the macro scale [63]. The combination of the ATIM and bistable mechanism could operate a digital compliant mechanism with two or three degrees of freedom.
REFERENCES


APPENDIX
Original computer programs are included here for reference. Section A.1 includes finite element models for the bistable mechanism and the second stage of NanoTran 3. Section A.2 contains programs that analyze SEM images and compile the results of resolution, repeatability, hysteresis, and drift tests.

A.1 Finite Element Models

The programs for the finite element models are written in the ANSYS Parametric Design Language (APDL) [110]. ANSYS builds, meshes, and solves each model according to the parameters specified at the beginning of the program. The programs may be executed as written to duplicate results or with modified parameters to analyze similar mechanisms. Several features may be valuable for inclusion in other models. For example, the program for NanoTran 3 creates a table of temperature-dependent material property values from an arbitrary empirical relation, reads temperature data from a text file generated by the finite difference thermal model, and applies the temperatures to individual nodes.
A.1.1 Bistable Mechanism

! FULLY COMPLIANT BISTABLE MECHANISM
! FINITE ELEMENT MODEL
! INCLUDING TEMPERATURE CHANGE

NEAL HUBBARD
23 AUG 2004

DESCRIPTION
This ANSYS finite element model finds the second stable equilibrium position of an FCBM and the change in position as a function of temperature. Only half of the mechanism is modeled. The temperature is assumed to be uniform throughout the mechanism. ANSYS reports the displacement, force, temperature, and maximum tensile stress at each load step. Watch force results to ensure that the mechanism moves to the stable (not the unstable) equilibrium position before the temperature is increased.

MODIFICATIONS

<table>
<thead>
<tr>
<th>DATE</th>
<th>NAME</th>
<th>DESCRIPTION OF CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Aug 2003</td>
<td>Neal Hubbard</td>
<td>Change parameter names</td>
</tr>
<tr>
<td>27 Aug 2003</td>
<td>Neal Hubbard</td>
<td>Modify solution controls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Add temperature steps</td>
</tr>
<tr>
<td>21 Aug 2004</td>
<td>Neal Hubbard</td>
<td>Modify for nanopositioner analysis</td>
</tr>
<tr>
<td>23 Aug 2004</td>
<td>Neal Hubbard</td>
<td>Modify output and comments</td>
</tr>
<tr>
<td>31 Aug 2004</td>
<td>Neal Hubbard</td>
<td>Remove segment 2a, new uniform temp., temperature dependent CTE</td>
</tr>
</tbody>
</table>

FINISH
/CLEAR,START
/TITLE,Fully-Compliant Bistable Mechanism

DEFINE THE MODEL
/PREP7
Unit system is micrometer, micronewton, megapascal, Celsius
Constants
pi=ACOS(-1)
dr=pi/180       !Degree-to-radian conversion
difCK=273.15    !Difference between Celsius and Kelvin scales

!Input
Tr=22           !Room temperature
Tunif=494.665   !Uniform temperature

!Design parameters
L1=64.2         !Length of the vertical segment
L2=95.7         !Length of segment 2
L3=146.4        !Length of segment 3
L4=77.3         !Length of segment 4
h1=3.5          !In-plane thickness of segment 1
h2=2.5                   !In-plane thickness of segment 2
h3=10                    !In-plane thickness of segment 3
h4=2.5                   !In-plane thickness of segment 4

b1=3.5                   !Out-of-plane thickness of segment 1
b2=b1                    !Out-of-plane thickness of segment 2
b3=b1                    !Out-of-plane thickness of segment 3
b4=b1                    !Out-of-plane thickness of segment 4

thetad2=7                !Angle of segment 2 (degrees)
thetad3=6                !Angle of segment 3 (degrees)
thetad4=7                !Angle of segment 4 (degrees)

!Material properties: Polysilicon
Em=160E3                  !Modulus of elasticity
PR=0.22                   !Poisson's ratio

!FEM parameters
meshscale=4               !Mesh refinement scale factor
ldiv1=4*meshscale         !Number of elements on half of line 1
ldiv2=12*meshscale        !Number of elements on line 2
ldiv3=5*meshscale         !Number of elements on line 3
ldiv4=10*meshscale        !Number of elements on line 4
psec=52                   !Estimated second stable position
ndisp=5                   !No. steps to estimated second stable position
ntemp=5                   !Number of temperature steps

!======================================================================
!                             BUILD THE MODEL
!======================================================================

!Define the element type and beam properties.
!(ET, Ref #, Element Name, Keyopt values)
ET,1,BEAM3
!(R, Real constant set, Area, Moment of inertia, Height, Shearz, 
!Prestrain, Mass property)
R,1,b1*h1,b1*(h1**3)/12,h1,1.2,0,0
R,2,b2*h2,b2*(h2**3)/12,h2,1.2,0,0
R,3,b3*h3,b3*(h3**3)/12,h3,1.2,0,0
R,4,b4*h4,b4*(h4**3)/12,h4,1.2,0,0

!Define material properties
!Coefficient of thermal expansion
TK=Tunif+difCK
CTE=(3.725*(1-EXP(-5.88E-3*(TK-124)))+5.548E-4*TK)*1E-6
!(MP, Material property type, Reference #, Zeroth- to fourth-order 
!coefficients in a property vs temperature polynomial)
MP,EX,1,Em
MP,PRXY,1,PR
MP,ALPX,1,CTE

!Define temperatures
nLs=ndisp+ntemp+1          !Total number of load steps
TREF,Tr                   !Reference temperature for thermal strain
!(*DIM, Name of array, array type, # rows, # columns, # planes, Names 
of index vectors)
*DIM,Tmp, ,nLs
!(*VFILL, Vector, Fill function, Input values)
*VFILL, Tmp(1), RAMP, Tr, 0

! Place key points.
theta2 = theta2 * dr      ! Angle of segment 2 (radians)
theta3 = theta3 * dr      ! Angle of segment 3 (radians)
theta4 = theta4 * dr      ! Angle of segment 4 (radians)
kp4x = L2 * COS(theta2)
kp4y = L2 * SIN(theta2)
kp5x = kp4x + L3 * COS(theta3)
kp5y = kp4y + L3 * SIN(theta3)
kp6x = kp5x + L4 * COS(theta4)
kp6y = kp5y + L4 * SIN(theta4)
!(K, Key point #, X-coordinate, Y, Z)
K, 1, 0, -L1/2
K, 2, 0, L1/2
K, 3, 0, 0
K, 4, kp4x, kp4y
K, 5, kp5x, kp5y
K, 6, kp6x, kp6y

! Draw lines.
!(L, Beginning key point, Ending key point)
L, 1, 3     ! Line 1
L, 2, 3     ! Line 2
L, 3, 4     ! Line 3
L, 4, 5     ! Line 4
L, 5, 6     ! Line 5

! Divide the lines into segments.
!(LESIZE, Line #, Division length, Division arc, Number of divisions,
! Spacing ratio, Kforc, Layer1, Layer2, Kyndiv)
LESIZE, 1, , , ldiv1
LESIZE, 2, , , ldiv1
LESIZE, 3, , , ldiv2
LESIZE, 4, , , ldiv3
LESIZE, 5, , , ldiv4

! Mesh the lines with beam elements.
!(TYPE, Element type number)
TYPE, 1
!(MAT, Material number)
MAT, 1
!(REAL, Real constant set number)
REAL, 1
!(LMESH, First line #, Last line #, Increment)
LMESH, 1, 2, 1
REAL, 2
LMESH, 3
REAL, 3
LMESH, 4
REAL, 4
LMESH, 5

! Reduce the displayed length of elements
/SHRINK, .5
! Turn off the global coordinate system triad
/TRIAD, OFF
! Fit geometry plot to screen
/AUTO, 1
!Display elements
EPLLOT

!Find the number of the node at the shuttle.
!(KSEL, Key points to select, Item label, Component label, Minimum
!value, Maximum value, Increment, Absolute value key)
KSEL,S,KP, ,6
!(NSLK, Subset of nodes to select)
NSLK,S
!(*GET, Variable, Entity, Entity number, Item name, Item label)
*GET,shuttle,NODE,0,NUM,MAX
!(NSEL, Nodes to select, Item label, Component label, Minimum value,
!Maximum value, Increment, Absolute value key)
NSEL,ALL
KSEL,ALL
FINISH

!======================================================================
!                             SOLVE THE MODEL
!======================================================================
/SOLU
!(ANTYPE, Analysis type, Status, Load step for a multiframe restart,
!Substep, Action)
ANTYPE,STATIC
!(SOLCONTROL, Optimized defaults, Check contact state, Pressure load
!stiffness, Volumetric compatibility tolerance)
SOLCONTROL,ON
!(NLGEOM, Large deformation effects) Stress stiffening is also active.
NLGEOM,ON
!(NROPT, Newton-Raphson option, Unused, Adaptive descent key)
NROPT,FULL, ,OFF
!(NSUBST, Size of the first substep in each load step, Maximum number
!of substeps, Minimum number, Carry-over key)
NSUBST,1,10,1,ON
!(AUTOTS, Automatic time stepping)
AUTOTS,ON
!(CNVTOL, Label, Convergence value, Tolerance about value, Norm,
!Minimum for the program-calculated reference value)
CNVTOL,F, ,.0001, ,1
CNVTOL,U, ,.0001, ,.1

!Apply constraints
!(DK, Key point #, DoF label, First value of the DoF, Second value,
!Expansion key, 5 additional DoF labels that will have the same value)
DK,1,ALL,0, ,0
DK,2,ALL,0, ,0
DK,6,UX,0, ,0,ROTZ

*IF,ndisp,GT,0,THEN
!Apply incremental displacements to the center shuttle.
dy=-psec/ndisp        !Step size for applied displacements
*DO,Lsn,1,ndisp
   DK,6,UY,Lsn*dy
*ENDDO
*ENDIF

191
!Release the shuttle so it snaps to the equilibrium position.
DKDEL,6,UY
LSWRITE,ndisp+1

*IF,ntemp,GT,0,THEN
!Increase the temperature incrementally.
dT=(Tunif-Tr)/ntemp !Temperature increment
LSEL,ALL
*DO,Lsn,ndisp+2,nLs
   Tmp(Lsn)=Tr+(Lsn-ndisp-1)*dT
!(BFL, Line #, Label, Value or X component, Y component, Z component, !Phase angle)
   BFL,ALL,TEMP,Tmp(Lsn)
   LSWRITE,Lsn
*ENDDO
*ENDIF

!Solve all load steps
LSSOLVE,1,nLs,1

!======================================================================
!                             REPORT RESULTS
!======================================================================
/POST1
!Output the shuttle displacement and force and the maximum stress.
*DIM,Disp, ,nLs
*DIM,Force, ,nLs
*DIM,Sten, ,nLs
*DIM,Scom, ,nLs
*DIM,Smax, ,nLs

!(ETABLE, Label for table, Item, Component)
ETABLE,smxi,NMIS,1
ETABLE,smxj,NMIS,3
ETABLE,smni,NMIS,2
ETABLE,smnj,NMIS,4

*DO,Lsn,1,nLs
!(SET, Load step, Substep, Scale factor, Complex component, Time, !Angle, Data set number)
   SET,Lsn
   *GET,disp(Lsn),NODE,shuttle,U,Y
   disp(Lsn)=-disp(Lsn)
   *GET,force(Lsn),NODE,shuttle,RF,FY
   force(Lsn)=-force(Lsn)
   ETABLE,REFL
!(ESORT, ETAB, Element table, Ascending order, Absolute value, Number !of elements)
   ESORT,ETAB,smxi,0,0
   *GET,maxi,SORT,0,MAX
   ESORT,ETAB,smxj,0,0
   *GET,maxj,SORT,0,MAX
   ESORT,ETAB,smni,0,0
   *GET,mini,SORT,0,MIN
   ESORT,ETAB,smnj,0,0
   *GET,minj,SORT,0,MIN
   Sten(Lsn)=MAX(maxi,maxj)
Scom(Lsn)=MIN(mini,minj)
Smax(Lsn)=MAX(Sten(Lsn),-Scom(Lsn))
*ENDDO

Range=ABS(Disp(nLs)-Disp(ndisp+1))

!(/OUTPUT, Filename, Extension, Directory, Location in file)
/OUTPUT, ResTmp, txt
*MSG, 'Step', 'Displacement', 'Force', 'Temperature', 'Tensile Stress'
%4C %14C %14C %14C %14C
*VWRITE, SEQU, Disp(1), Force(1), Tmp(1), Sten(1)
%5I %14.6F %14.6F %14I %14.3F
*MSG, '
%C
*MSG, 'Second', Disp(ndisp+1)
%6C Stable Equilibrium Position %/ %6.1F µm
*MSG, 'Maximum', Disp(nLs)
%7C Displacement %/ %6.1F µm
*MSG, 'Range', Range
%5C of Second Stage %/ %6.1F µm
/OUTPUT

!Create a color plot of stress.
!(/DSCALE, Window number, Displacement scale factor)
/DSCALE, 1, 1
PLETAB, smxj, NOAV
FINISH

A.1.2 NanoTran 3

!NanoTran 3
!Finite Element Model
!Neal Hubbard
!8 Sep 2004

The displacement and maximum stress of the second stage of NanoTran 3 are calculated. The input temperature may be a single value to be applied uniformly to the expansion beam or a temperature distribution supplied by the finite difference thermal model (FDM).

FINISH
/CLEAR, NOSTART

!----------------------- Input Parameters -----------------------------
/PREP7
!Units are micrometer, kilogram, second, micronewton, Celsius, and megapascal.

!Constants
difCK = 273.15 !Difference between Celsius and Kelvin scales

!Design parameters for the NanoTran 3 TIM
Lex = 204 !X-component of expansion beam length
Ley = 14.3 !Y-component of expansion beam length (offset)
Ls = 11 !Length of shuttle (x direction)
Lp = 100 !Length of pad (x direction)
Lax = 7                 !X-component of amplifying beam length
Lay = 199               !Y-component of amplifying beam length
Lf = 200                !Flexure length
we = 3                  !Width of expansion beams
ws = 30                 !Width of TIM shuttle (y direction)
wp = 30                 !Width of pad (y direction)
wa = 3                  !Width of amplifying beams
wf = 3                  !Width of flexures
t = 3.5                 !Out-of-plane thickness of the entire model
ne = 32                 !Number of expansion beams
na = 8                  !Number of amplifying beams
nf = 6                  !Number of flexures

!Material properties
Em = 160E3              !Modulus of elasticity for polysilicon
PR = 0.22               !Poisson's ratio for polysilicon

!Input parameters
Tr = 22                 !Room temperature
distmp = 1              !Option to apply the true temperature
!distribution (1) or a uniform temperature (0)
Tunif = 537             !Uniform temperature applied to expansion beam
ebonly = 0              !Option to apply temperature to the expansion
!beam only (1), or to the pad, expansion beam,
!and shuttle (0). This option only applies to
!the true temperature distribution.
gap = 0.4               !Gap between the TIM and the second stage

!FEM parameters
MRF = 1                 !Mesh refinement factor
!Number of elements on each beam
NEP = 10*MRF            !Pad
NEE = 102*MRF           !Expansion beam
NES = 2*MRF             !Half of TIM shuttle
NEA = 199*MRF           !Amplifying beam
NEF = 40*MRF            !Flexure
NLS = 4                 !Number of load steps

!----------------------- Build the Solid Model ------------------------
!Place key points.
kp2x = Lp
kp2y = 0
kp3x = kp2x+Lex
kp3y = Ley
kp4x = kp3x+Ls/2
kp4y = kp3y
kp5x = kp4x+Lax
kp5y = kp4y+Lay
kp6x = kp4x+Lf
kp6y = kp4y
 !(K, Key point #, X-coordinate, Y, Z)
K,1,0,0                  !Anchor
K,2,kp2x,kp2y           !Left end of expansion beam
K,3,kp3x,kp3y           !Right end of expansion beam
K,4,kp4x,kp4y           !TIM shuttle
K,5,kp5x,kp5y           !Second stage
K,6,kp6x,kp6y           !First-stage frame
!Draw lines.
!(L, Beginning key point, Ending key point)
L,1,2                   !Line 1, Pad
L,2,3                   !Line 2, Expansion beam
L,3,4                   !Line 3, Half of TIM Shuttle
L,4,5                   !Line 4, Amplifying beam
L,4,6                   !Line 5, Flexure

!Divide the lines into segments.
!(LESIZE, Line #, Division length, Division arc, Number of divisions,
!Spacing ratio, Kforc, Layer1, Layer2, Kyndiv)
LESIZE,1, , , , , ,NEP
LESIZE,2, , , , , ,NEE
LESIZE,3, , , , , ,NES
LESIZE,4, , , , , ,NEA
LESIZE,5, , , , , ,NEF

!----------------------- Build the Finite Element Model ---------------
!Element type
!(ET, Ref #, Element Name, Keyopt values)
ET,1,BEAM3

!Material properties
!(MP, Material property type, Reference #, Zeroth- to fourth-order
!coefficients in a property vs temperature polynomial)
MP,EX,1,Em
MP,PRXY,1,PR
TREF,Tr                 !Reference temperature for thermal strain

!Create tables of temperatures and corresponding material properties
templim = Tr+900        !Temperature limit for property definitions
numtemp = 46            !Number of temperature values to define
tempinc = (templim-Tr)/(numtemp-1) !Temperature increment
!(*DIM, Name of array, array type, # rows, # columns, # planes, Names
!of index vectors)
*DIM,TC, ,5             !Temporary array for Celsius temperature
*DIM,CTE, ,5            !Temporary array for CTE
TC(1) = Tr
TK = TC(1)+difCK
CTE(1) = (3.725*(1-EXP(-5.88E-3*(TK-124)))+5.548E-4*TK)*1E-6
!(MPTEMP, Index, Six temperatures to list in MPDATA)
MPTEMP,1,TC(1)
!(MPDATA, Label, Material, Index, Six property values)
MPDATA,ALPX,1,1,CTE(1)
*DO,i,2,numtemp,5
  *DO,j,1,5
    TC(j) = Tr+(i+j-2)*tempinc
    TK = TC(j)+difCK
    CTE(j) = (3.725*(1-EXP(-5.88E-3*(TK-124)))+5.548E-4*TK)*1E-6
  *ENDDO
MPTEMP,i,TC(1),TC(2),TC(3),TC(4),TC(5)
MPDATA,ALPX,1,i,CTE(1),CTE(2),CTE(3),CTE(4),CTE(5)
*ENDDO

!Beam properties
!(R, Real constant set, Area, Moment of inertia, Height, Shearz,
!Prestrain, Mass property)
R,1,ne*t*wp,ne*t*wp**3/12,wp,1.2 !Pad
R,2,ne't*we,ne't*we**3/12,we,1.2 !Expansion beam
R,3,ne't*ws,ne't*ws**3/12,ws,1.2 !TIM Shuttle
R,4,na't*wa,na't*wa**3/12,wa,1.2 !Amplifying beam
R,5,nf't*wf,nf't*wf**3/12,wf,1.2 !Flexure

!Mesh the lines with beam elements.
TYPE,1
MAT,1
REAL,1                  !Pad
!(LMESH, First line #, Last line #, Increment)
LMESH,1
REAL,2                  !Expansion beam
LMESH,2
REAL,3                  !TIM Shuttle
LMESH,3
REAL,4                  !Amplifying beam
LMESH,4
REAL,5                  !Flexure
LMESH,5

!Find anchor node
KSEL,S,KP, ,1
NSLK,S
!*GET, Variable, Entity, Entity number, Item name, Item label)
*GET,anchor,NODE,0,NUM,MAX

!Find nodes at each end of expansion beam
KSEL,S,KP, ,2
NSLK,S
*GET,ebleft,NODE,0,NUM,MAX
KSEL,S,KP, ,3
NSLK,S
*GET,ebright,NODE,0,NUM,MAX

!Find node at center of TIM shuttle
KSEL,S,KP, ,4
NSLK,S
*GET,TIMshuttle,NODE,0,NUM,MAX

!Find node on second stage (symmetry point)
KSEL,S,KP, ,5
NSLK,S
*GET,stage2,NODE,0,NUM,MAX

!Find node on first-stage frame
KSEL,S,KP, ,6
NSLK,S
*GET,stage1,NODE,0,NUM,MAX
KSEL,ALL
NSEL,ALL                !Reselect all nodes for subsequent analysis

!Display elements at half length.
/SHRINK,.5
!Omit the global coordinate system from plots
/TRIAD,OFF
EPLOT

!----------------------- Input the Temperature Distribution -----------
*IF, distmp, EQ, 1, THEN

nnf dm = 62 ! Number of nodes in the finite difference model
ncol = 2 ! Number of columns in temperature data file
Tcol = 2 ! Column number of temperature data
deltax = 10 ! Length increment between nodes in the FDM

! Include a node across the symmetry line if necessary to allow
! interpolation of property values up to the symmetry line.
! The number of rows in the temperature data file is nrow; it is also
! the number of nodes on one side of the symmetry line. The number of
! values to store in the temperature table is nval.
rmnd = MOD(nnf dm, 2)
*IF, rmnd, EQ, 0, OR, rmnd, EQ, 2, THEN
   nrow = NINT(nnf dm/2)
   nval = nrow + 1
*ELSE
   nrow = NINT((nnf dm-rmnd)/2+1)
   nval = nrow
*ENDIF

*DIM, pos, , nval ! Position relative to the anchor point
*DIM, Tdata, , nrow, ncol ! Temperatures from data file
!*VFILL, Vector, Fill function, Input values)
*VFILL, pos(1), RAMP, 0, deltax
*DIM, Tdist, TABLE, nval
*DO, i, 1, nval
   Tdist(i, 0) = pos(i) ! Assign row indices
*ENDDO
Tdist(0, 1) = 1 ! Assign column index
Tdist(0, 0) = 1 ! Assign plane index

!*VREAD, Name of array, File name, Extension, Directory, Index
! order, First, second, and third index limits, Lines to skip)
*VREAD, Tdata(1, 1), NT3_Tprf25700, txt, , JIK, ncol, nrow, 1, 4
! (E4.0, E13.0)

! The temperature distribution is not imported with the *TREAD
! command because the temperature table must be dimensioned with an
! additional node across the symmetry line. The *TREAD command is not
! affected by *VLEN and would have to read the data into a temporary
! table, which would then be copied into the table Tdist. *VREAD
! creates the temporary array Tdata, which is simpler to dimension
! than a table because it does not require vectors of subscripts. A
! second reason to use *VREAD instead of *TREAD is that *TREAD can
! only read text files that are saved in Unix format; *VREAD handles
! both Unix and Windows text files.

! Ensure that the additional node beyond the symmetry line (if it
! exists) takes on the temperature of the symmetric node
Tdist(nval) = Tdata(nrow, Tcol)
! Fill the elements up to the symmetry line
*DO, i, 1, nrow
   Tdist(i) = Tdata(i, Tcol)
*ENDDO

! Find the temperature of each node on the pad, expansion beam, or
! TIM shuttle according to its x coordinate
Tpeak = Tr
*IF, ebonly, EQ, 0, THEN
   ! Select nodes on the pad, expansion beam, and TIM shuttle
   *(LSEL, Type, Item, Component, Minimum value, Maximum value,
!Increment, Option to include associated key points, nodes, and
!elements)
LSEL,S,REAL, ,1,3,1,0
!(NSLL, Type, Option to include end nodes)
NSLL,S,1
*ELSE
!Select nodes on the expansion beam only
LSEL,S,REAL, ,2, , ,0
NSLL,S,1
*ENDIF
*GET,nfirst,NODE,0,NUM,MIN !First node in selected set
*GET,ncount,NODE,0,COUNT !Number of nodes in selected set
*DIM,nodenum, ,ncount !Node numbers in increasing order
*DIM,xcoord, ,ncount !X coordinate of each node
*DIM,Tfinal, ,ncount !Final temperature of each node
nodenum(1) = nfirst
*DO,nidx,1,ncount
   xcoord(nidx) = NX(nodenum(nidx))
   Tfinal(nidx) = Tdist(xcoord(nidx))
   *IF,Tfinal(nidx),GT,Tpeak,THEN
      Tpeak = Tfinal(nidx) !Peak temperature
   *ENDIF
*IF,nidx,EQ,ncount,EXIT
   nodenum(nidx+1) = NDNEXT(nodenum(nidx))
*ENDDO
LSEL,ALL !Reselect all lines
NSEL,ALL !Reselect all nodes for subsequent analysis

/OUTPUT,TempCheck,txt
*MSG, ,'Tdata'
%-20C
*VWRITE,Tdata(1,1),Tdata(1,2)
%4.0F %12.3F
*MSG, ,'Tdist'
%/ %-20C
*VWRITE,pos(1),Tdist(1,1)
%4.0F %12.3F
*MSG, ,'Nodes,'
%/ %6C x coordinates, and temperatures
*VWRITE,nodenum(1),xcoord(1),Tfinal(1)
%4.0f %14.3F %16.3F
/OUTPUT
*ENDIF
FINISH

!----------------------- Solve the Model ------------------------------
/SOLU
!(ANTYPE, Analysis type, Status, Load step for a multiframe restart,
!Substep, Action)
ANTYPE,STATIC
SOLCONTROL,ON
!(NLGEOM, Large deformation effects) Stress stiffening is also active.
NLGEOM,ON !Account for large deflections.
!(NROPT, Newton-Raphson option, Unused, Adaptive descent key)
NROPT,FULL, ,OFF
!(NSUBST, Size of the first substep in each load step, Maximum number
!of substeps, Minimum number, Carry-over key)
NSUBST,1,10,1,ON

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!(AUTOTS, Automatic time stepping)
AUTOTS,ON

!(CNVTOL, Label, Convergence value, Tolerance about value, Norm, !Minimum for the program-calculated reference value)
CNVTOL,F, ,.0001, ,1
CNVTOL,U, ,.0001, ,.01

!Apply constraints
!(D, First node, DoF label, First value, Second value, Last node, !Increment, 5 additional DoF labels)
D,anchor,UX,0, , , ,ROTZ
D,anchor,UY,-gap
D,TIMshuttle,UX,0, , , ,ROTZ
D,stage2,UY,0, , , ,ROTZ
D,stage1,UY,0, , , ,ROTZ

*DIM,Tpeakls, ,NLS !Peak temperature in each load step
*IF,distmp,EQ,1,THEN
  !Apply the temperature distribution incrementally
  *DO,i,1,NLS
    Tpeakls(i) = (Tpeak-Tr)*i/NLS+Tr
  *DO,nidx,1,ncount
    !BF, Node, Label, Up to four values as required by label
    BF,nodenum(nidx),TEMP,(Tfinal(nidx)-Tr)*i/NLS+Tr
  *ENDDO
  LSWRITE,i
*ENDDO
*ELSE
  !Apply uniform temperature incrementally to the expansion beam
  !(ESEL, Type of select, Item label, Component label, Minimum value, !Maximum value, Increment, Absolute value key)
  ESEL,S,REAL, ,2 !Select elements on the expansion beam
  *DO,i,1,NLS
    Tpeakls(i) = (Tunif-Tr)*i/NLS+Tr
  !(BFE, Element, label, Index, Four values)
  BFE,ALL,TEMP,1,Tpeakls(i) !Apply temperature to selected elements
  LSWRITE,i
  *ENDDO
  ESEL,ALL !Reselect all elements
*ENDIF

!Solve all load steps
LSSOLVE,1,NLS
FINISH

!----------------------- Compile Results ------------------------------
/POST1

*DIM,ds, ,NLS !Displacement of second stage
*DIM,TIMds, ,NLS !TIM shuttle displacement
*DIM,axforce, ,NLS !Axial force on TIM (y direction)
*DIM,trforce, ,NLS !Transverse force on TIM (x direction)
*DIM,abforce, ,NLS !Axial force in amplifying beam (y dir.)
*DIM,abfr, ,NLS !Fraction of TIM axial force from amplif. beam
*DIM,flforce, ,NLS !Transverse force on flexure (y direction)
*DIM,flfr, ,NLS !Fraction of TIM axial force from flexure
*DIM,padexp, ,NLS !Expansion of the pad
*DIM,shexp, ,NLS !Expansion of the shuttle, including full width
*DIM,sten, ,NLS !Tensile stress
*DIM,scom, ,NLS       !Compressive stress
*DIM,smax, ,NLS       !Maximum principal stress

!(ETABLE, Label for table, Item, Component)
ETABLE,smxi,NMIS,1
ETABLE,smxj,NMIS,3
ETABLE,smni,NMIS,2
ETABLE,smnj,NMIS,4

*DO,i,1,NLS
!Select load step
!(SET, Load step, Substep, Scale factor, Complex component, Time, !Angle, Data set number)
SET,i
!Find displacements and forces
ds(i) = UX(stage2)
TIMds(i) = UY(TIMshuttle)+gap
*GET,axforce(i),NODE,anchor,RF,FY
*GET,trforce(i),NODE,anchor,RF,FX
*GET,abforce(i),NODE,stage2,RF,FX
abforce(i) = -abforce(i)
abfr(i) = abforce(i)/axforce(i)
*GET,flforce(i),NODE,stage1,RF,FY
flfr(i) = flforce(i)/axforce(i)

padexp(i) = UX(ebleft)
shexp(i) = -2*UX(ebright)

!Find stresses
ETABLE,REFL
!(ESORT, ETAB, Element table, Ascending order, Absolute value, !Number of elements)
ESORT,ETAB,smxi,0,0
*GET,maxi,SORT,0,MAX
ESORT,ETAB,smxj,0,0
*GET,maxj,SORT,0,MAX
ESORT,ETAB,smni,0,0
*GET,mini,SORT,0,MIN
ESORT,ETAB,smnj,0,0
*GET,minj,SORT,0,MIN

!If the maximum stress is less than zero, the maximum tensile stress !occurs in the z direction, where it is zero. Similarly, if the !minimum stress is greater than zero, the maximum compressive stress !occurs in the z direction, where it is zero.
Sten(i) = MAX(MAX(maxi,maxj),0)
Scom(i) = MIN(MIN(mini,minj),0)
Smax(i) = MAX(Sten(i),-Scom(i))

*ENDDO

!----------------------- Report Results -------------------------------
!/OUTPUT, Filename, Extension, Directory, Location in file)
/OUTPUT,NT3FEA25700,txt
*MSG,INFO,'NanoTran 3'
%10C Second Stage Finite Element Analysis %/
*MSG,INFO,'Peak Temp.','Displacement','Ten. Stress','Com. Stress'
Step %14C %14C %14C %14C
VWRITE,SEQU,Tpeakls(1),ds(1),sten(1),scom(1)
(F5.0,4F15.6)
The finite element model above reads the temperature distribution from a file named “NT3_Tprf25700.txt” that contains the following:

Temperature profile to be read by the finite element model
Includes one pad, one expansion beam, and half of the shuttle
Total current is 25.7 mA

Node  Temperature
1     22.000
2     32.898
3     43.797
4     54.695
5     65.594
6     76.493
7     87.392
8     98.292
9    109.192
10   120.093
11   130.994
12   167.503
13   204.288
14   241.684
15   279.972
16   319.382
17   360.088
18   402.189
19   445.694
20   490.493
21   536.330
A.2 Data Analysis Tools

The program that analyzes SEM images to make position measurements is listed in Section A.2.1. The programs in Sections A.2.2–A.2.5 are post processors that determine the results of resolution, repeatability, hysteresis, and drift tests. The image processor and post processors are Matlab scripts [116]. Parameters specified at the beginning of each script control the execution of nearly every function in the remainder of the script.

The image processor reads a sequence of files with file names that differ only by an index number. It handles grayscale intensity images, indexed color images, and true color (RGB) images. Color images are converted to grayscale images for processing. The image processor has several options that help identify the edges of the objects in the images. First, the images may be cropped at a specified location and size. Second, a subset of the column indices may be selected for the search routine. It may be a combination of disjoint segments of the grayscale profile. This option allows the search routine to avoid regions with excessive noise. Third, the image processor is able to select the edges on the left sides of the objects, on the right sides, or both. Selecting only one side of each object reduces the number of peaks in the derivative data and simplifies the process of locating the objects. Fourth, sharp spikes in the derivatives may be rejected by requiring the derivative to exceed the threshold value for a number of consecutive points before a peak is
counted as the edge of an object. Fifth, a unique derivative threshold may be specified for each edge that the program encounters. Small peaks may be skipped by setting the threshold slightly above them; significant peaks rise above the threshold.

The output of the image processor is a list of position measurements. The post processors compute displacements from the position measurements and evaluate the definitions of resolution, repeatability, hysteresis, and drift. They create plots of the results and export them in convenient image file formats. The post processor for the repeatability test utilizes a script in the statistics toolbox named “tinv” that may not be available with all Matlab licenses.

The image processor may need to be executed twice for a single test because the measurements usually fall into two groups. The positions measured with zero input current form the first group. The second group consists of the measurements that indicate the performance of the nanopositioner. The displacement corresponding to each measurement in the second group is found by subtracting the average zero-current position from it, as is explained in Section 5.2.1.

A.2.1 Image Processor

% Image Processor
%A tool for extracting position measurements from scanning electron micrographs
% Neal Hubbard
% 16 Dec 2004

%----------------------- Parameters -----------------------------------------
% Image File Names
% The size and type of each image file must be the same.
% The directory path may be complete, or it may contain only the subdirectories within the working directory.
fndir = 'Cropped\'; % Directory path (including final backslash)
fnpfx = 'NT3Ares'; % File name prefix
fnsfx = ''; % File name suffix
fnext = 'tif'; % File name extension
imn = [10:59]';
%List of image numbers to process
imndig = 2;
%Maximum number of digits in the image number
% (If 0, only one image is processed)
padchar = '0';
%Character with which to pad the image number
%(0 or blank)

%Orientation
motndir = 2;
%Measurement direction (1 for vertical, 2 for horizontal)

%Crop
%Image dimensions are given as [height width] because the first dimension of
%an image array indexes in the vertical direction and the second in the
%horizontal direction.
cropimg = logical(0);
%Option to process a region within the image (0 or 1)
topleft = [40 315];
%Top left corner of the region to process [top left]
crpsize = [250 700];
%Size of the region to process [height width]

%Image adjustment
brtcnt = logical(0);
%Option to adjust brightness and contrast (0 or 1)
ltrreg = [170 220];
%Profile indices delimiting the light region
dkreg = [350 550];
%Profile indices delimiting the dark region
shift = .51;
%Average grayscale value of the dark region after
%adjustment
scale = .03;
%Difference between the average values of the light
%and dark regions after adjustment

%Edge detection
search = [50:200,550:700];
%Range of profile indices to search
%Enter an empty array to search the entire image.
%Enter a decreasing array to search backwards.
sgnder = 1;
%Sign of derivative to detect (1 for positive, 2 for
%negative, 3 for both)
consec = 2;
%Minimum number of consecutive points per edge
%Edges must contain at least 2 points in order to be
%located accurately.
derth = .025;
%Threshold derivative(s) for edge identification
%The threshold is always positive. It may be a
%scalar, in which case it is used for all edges, or
%it may be a vector containing a separate threshold
%for every edge that the program will encounter
%during the search.
movedg = 1;
%Moving edge number, counting from the left or top
fixedg = 2;
%Fixed edge number, counting from the left or top
%The search stops when both the moving and fixed
%edges have been identified.
bench = .61;
%Benchmark grayscale value(s)
%The benchmark may be a scalar, in which case it is
%applied to all edges, or it may be a vector
%containing a separate benchmark for each edge.

%Align profiles along fixed edges
align = logical(1);
%Option to align the profiles for display purposes
fixpos = 620;
%Position at which to align the fixed edges

%Calibration
%The unit of length is the micrometer.
calib = 52.839;
%Calibration factor (pixels/μm)
%General options
saveresults = logical(1); %Save results
diagnose = logical(1); %Print diagnostic output to screen
originalplot = logical(1); %Plot original grayscale profiles
derivativeplot = logical(1); %Plot derivatives of grayscale profiles
grayimage = logical(0); %Display last grayscale image
savegrayimage = logical(0); %Save last grayscale image in TIF format
profileplot = logical(1); %Plot adjusted grayscale profiles
positionplot = logical(1); %Plot relative position of moving object

%----------------------- Preliminary Steps ----------------------------------
begtime = clock; %Record the beginning time
disp(' '); disp('Image Processor')
maxnedg = max([movedg; fixedg]); %Maximum number of edges to locate

%Ensure that the threshold list contains enough values for all of the
%anticipated edges
if length(derth) == 1
    derth = derth.*ones(1,maxnedg);
else if length(derth) < maxnedg
    disp('The number of derivative thresholds is insufficient to define')
    disp('all of the edges that the program is required to find.')
    disp(['At least ',num2str(maxnedg,'%3.0f'), ...]
         ' thresholds and benchmarks must be specified.'])
    return
end

%Ensure that the benchmark list contains enough values for all of the
%anticipated edges
if length(bench) == 1
    bench = bench.*ones(1,maxnedg);
else if length(bench) < maxnedg
    disp('The number of benchmark grayscale values is insufficient to')
    disp('define all of the edges that the program is required to find.')
    disp(['At least ',num2str(maxnedg,'%3.0f'), ...]
         ' thresholds and benchmarks must be specified.'])
    return
end

%Specify the image number format for file names
imnfmt = strcat('%',padchar,num2str(imndig,'%1.0f'),'.0f');
%Concatenate the path and file name components
if imndig == 0
    fname = [fndir,fnpfx,fnsfx,'.',fnext];
    nimg = 1; %Only process one image
else
    fname = [fndir,fnpfx,num2str(imn(1),imnfmt),fnsfx,'.',fnext];
    nimg = length(imn); %Number of images to process
end

%Determine image size and type
[img,cmap] = imread(fname,fnext);
%The image size vector is set before the loop begins and is not changed
%within the image processing loop.
imgsize = size(img);
if ndims(img) > 2
    imgtype = 'truecolor';
%Limit imgsize to three elements and ensure that the third element is 3
imgsize = [imgsize(1:2),3];
disp('Image Type: True Color (RGB)')
else
  if isempty(cmap)
    imgtype = 'grayscale';
    disp('Image Type: Gray Scale')
  else
    imgtype = 'indexed';
    disp('Image Type: Indexed')
  end
end

if cropimg
  %Ensure that the region to be processed lies within the image
  %Size of region to be processed
  regsize = min(crpsize,imgsize(1:2)-topleft+1);
else
  regsize = imgsize(1:2);
end
npts = regsize(motndir); %Number of points in each grayscale profile

%Check that the range of profile indices to search is within the array bounds
if (min(search) < 1) | (max(search) > npts)
  disp('The specified range of grayscale profile indices for the edge')
  disp('search exceeds the bounds of the profiles. The indices must be')
  disp(['between 1 and ',num2str(npts,'%6.0f'),', inclusive.'])
  return
end

%Initialize arrays
profile = zeros(npts,2,nimg);   %Grayscale profiles with adjustments
orgprf = zeros(npts,nimg);      %Original grayscale profiles
der = zeros(npts,nimg);         %Derivatives of grayscale profiles
reloc = zeros(nimg,1);          %Relative location of moving edge (pixels)
position = zeros(nimg,1);       %Relative position of moving edge (µm)
edgind = zeros(2,maxnedg);      %Edge indices (first and last column numbers)
edgwid = zeros(nimg,maxnedg);   %Width of each edge (pixels)
edgloc = zeros(nimg,maxnedg);   %Edge locations relative to the left or top
ubound = zeros(nimg,maxnedg);   %Minimum grayscale value bounding each edge
lbound = zeros(nimg,maxnedg);   %Minimum grayscale value bounding each edge
middle = zeros(nimg,maxnedg);   %Grayscale value mid-way between the bounds

%----------------------- Process Images -------------------------------------
for m = 1:nimg %m is the image index
  tic %Begin loop timer
disp(['Processing image number ',num2str(imn(m),'%4.0f')])
  if m ~= 1
    %Update file name to include current image number
    fname = [fndir,fnpfx,num2str(imn(m),imnfmt),fnsfx,'.',fnext];
    %Read image file
    [img,cmap] = imread(fname,fnext);
    %Check the image size
    chksize = size(img);
    if sum(abs(chksize(1:2)-imgsize(1:2))) > 1E-3
      disp(['Image ',num2str(imn(m),'%4.0f'),', ...
        ' is not the same size as the first image'])
      disp('and cannot be processed in the same batch.')
      return
    end
  end

  %Initialize arrays
  profile = zeros(npts,2,nimg);   %Grayscale profiles with adjustments
  orgprf = zeros(npts,nimg);      %Original grayscale profiles
  der = zeros(npts,nimg);         %Derivatives of grayscale profiles
  reloc = zeros(nimg,1);          %Relative location of moving edge (pixels)
  position = zeros(nimg,1);       %Relative position of moving edge (µm)
edgind = zeros(2,maxnedg);      %Edge indices (first and last column numbers)
edgwid = zeros(nimg,maxnedg);   %Width of each edge (pixels)
edgloc = zeros(nimg,maxnedg);   %Edge locations relative to the left or top
ubound = zeros(nimg,maxnedg);   %Minimum grayscale value bounding each edge
lbound = zeros(nimg,maxnedg);   %Minimum grayscale value bounding each edge
middle = zeros(nimg,maxnedg);   %Grayscale value mid-way between the bounds

  %----------------------- Process Images -------------------------------------
  for m = 1:nimg %m is the image index
    tic %Begin loop timer
disp(['Processing image number ',num2str(imn(m),'%4.0f')])
    if m ~= 1
      %Update file name to include current image number
      fname = [fndir,fnpfx,num2str(imn(m),imnfmt),fnsfx,'.',fnext];
      %Read image file
      [img,cmap] = imread(fname,fnext);
      %Check the image size
      chksize = size(img);
      if sum(abs(chksize(1:2)-imgsize(1:2))) > 1E-3
        disp(['Image ',num2str(imn(m),'%4.0f'),', ...
          ' is not the same size as the first image'])
        disp('and cannot be processed in the same batch.')
disp(' ')  
continue  
end  
end  

%Remove extra dimensions  
while ndims(img) > 3  
    img(:,:,end) = [];  
end  

%Crop Image  
if cropimg  
    fullimg = img;  
    if ndims(fullimg) == 2  
        img = zeros(regsize);  
        for j = 1:regsize(2)  
            for i = 1:regsize(1)  
                img(i,j) = fullimg(i+topleft(1)-1,j+topleft(2)-1);  
            end  
        end  
    else  
        img = zeros([regsize,3]);  
        for k = 1:3  
            for j = 1:regsize(2)  
                for i = 1:regsize(1)  
                    img(i,j,k) = fullimg(i+topleft(1)-1,j+topleft(2)-1,k);  
                end  
            end  
        end  
    end  
else  
    img = zeros([regsize,3]);  
    for k = 1:3  
        for j = 1:regsize(2)  
            for i = 1:regsize(1)  
                img(i,j,k) = fullimg(i+topleft(1)-1,j+topleft(2)-1,k);  
            end  
        end  
    end  
end  
end  

%Convert the image to a gray scale with double-precision numbers ranging  
%from 0 to 1. Allow for different color types and bit depths.  
gryimg = zeros(regsize);  
switch imgtype  
case 'indexed'  
    %Convert color indices to standard array indices  
    img = double(img)+1;  
    %Reference RGB values in the color map and convert to grayscale  
    rgbset = zeros(3,1);  
    for j = 1:regsize(2)  
        for i = 1:regsize(1)  
            rgbset(:) = cmap(img(i,j),1:3);  
            gryimg(i,j) = [0.299 0.587 0.114]*rgbset;  
        end  
    end  
end  
case 'grayscale'  
    %Scale the intensity values to the range [0 1]  
    if isa(img,'uint8')  
        gryimg = double(img)/255;  
    elseif isa(img,'uint16')  
        gryimg = double(img)/65535;  
    else  
        gryimg = double(img);  
        gryimg = gryimg-min(gryimg(:));  
        gryimg = gryimg./max(gryimg(:));  
    end
case 'truecolor'
    %Scale the intensity values to the range [0 1]
    if isa(img,'uint8')
        img = double(img)./255;
    elseif isa(img,'uint16')
        img = double(img)./65535;
    else
        img = double(img);
        img = img-min(img(:));
        img = img./max(img(:));
    end
%Convert RGB values to grayscale
rgbset = zeros(3,1);
for j = 1:regsize(2)
    for i = 1:regsize(1)
        rgbset(:) = img(i,j,1:3);
        gryimg(i,j) = [0.299 0.587 0.114]*rgbset;
    end
end
end

%----------------------- Compute grayscale profile --------------------------
profile(:,1,m) = 1:npts;
if motndir == 1
    profile(:,2,m) = mean(gryimg');
else
    profile(:,2,m) = mean(gryimg);
end

%Store the original profile
orgprf(:,m) = profile(:,2,m);
%The column numbers for all of the original profiles are the integers from
%1 to npts, so they are not stored in orgprf.

%----------------------- Adjust Brightness and Contrast ---------------------
%Scale and shift the grayscale values such that the light and dark regions
%have the same average values in all the profiles
if brtcnt
    %Average value of the dark region
dkavg = mean(profile(dkreg(1):dkreg(2),2,m));
    %Average value of the light region
ltavg = mean(profile(ltreg(1):ltreg(2),2,m));
    profile(:,2,m) = (profile(:,2,m)-dkavg)./(ltavg-dkavg).*scale+shift;
end

%----------------------- Compute derivative of profile ----------------------
der(1,m) = profile(2,2,m)-profile(1,2,m);
for i = 2:npts-1
    der(i,m) = (profile(i+1,2,m)-profile(i-1,2,m))./2;
end
der(npts,m) = profile(npts,2,m)-profile(npts-1,2,m);
if sgnder == 2
    der(:,m) = -der(:,m);
else if sgnder == 3
    der(:,m) = abs(der(:,m));
end
%----------------------- Identify the Moving and Reference Edges ------------
enum = 0;               %Edge number
efnd = logical(0);      %Flag: edge located
edgind(:) = 0;
if isempty(search)
    search = [1:npts];
end
for subi = 1:length(search)
    i = search(subi);
    if efnd %Currently on an edge
        if der(i,m) <= derth(enum) %Edge ends
            edgind(2,enum) = search(subi-1); %Store second index
            efnd = logical(0);
            edgind(:,enum) = sort(edgind(:,enum),1); %Sort edge indices
            edgwid(m,enum) = edgind(2,enum)-edgind(1,enum)+1; %Edge width
            if edgwid(m,enum) < consec
                enum = enum-1; %Store next edge indices over current indices
            end
            if enum >= maxnedg %Maximum number of edges have been found
                break %Quit search
            end
        end
    else %Not currently on an edge
        if der(i,m) > derth(enum+1) %Edge found
            enum = enum+1;
            edgind(1,enum) = i; %Store first index
            efnd = logical(1);
        end
    end
end
ne = enum;              %Number of edges found

%Find the grayscale values bounding each edge
bounds = reshape(profile(edgind(:,1:ne),2,m),2,ne);
ubound(m,1:ne) = max(bounds);
lbound(m,1:ne) = min(bounds);
middle(m,1:ne) = mean(bounds);

%Check whether the fixed and moving edges have been identified
if ne < fixedg
    disp('The fixed edge was not found.')
end
if ne < movedg
    disp('The moving edge was not found.')
end

%----------------------- Position -------------------------------------------
%Interpolate to find edge locations
for enum = 1:ne
    cnum = edgind(1,enum):edgind(2,enum);
    coef = [ones(edgwid(m,enum),1),profile(cnum,1,m)]
          \profile(cnum,2,m);
    edgloc(m,enum) = (bench(enum)-coef(1))./coef(2);
end

%Relative position of the moving edge (in micrometers)
reloc(m) = edgloc(m,movedg)-edgloc(m,fixedg);
position(m) = reloc(m)./calib;
%----------------------- Align Profiles ---------------------------------------
if align
    profile(:,1,m) = profile(:,1,m)+fixpos-edgloc(m,fixedg);
end

%----------------------- Diagnostic Output -----------------------------------
if diagnose
    disp('First and last indices for each edge')
    disp(sprintf('%10.0f',edgind(1,1:ne)))
    disp(sprintf('%10.0f',edgind(2,1:ne)))
    disp('Edge locations')
    disp(sprintf('%10.3f',edgloc(m,1:ne)))
    disp('Edge widths')
    disp(sprintf('%10.0f',edgwid(m,1:ne)))
    disp('Derivative Thresholds')
    disp(sprintf('%10.3f',derth(1:ne)))
    disp('Grayscale values bounding each edge')
    disp(sprintf('%10.3f',ubound(m,1:ne)))
    disp(sprintf('%10.3f',lbound(m,1:ne)))
    disp('Benchmark grayscale value for each edge')
    disp(sprintf('%10.3f',bench(1:ne)))
    disp('Middle grayscale value for each edge')
    disp(sprintf('%10.3f',middle(m,1:ne)))
    disp(sprintf('Relative Location: %11.3f pixels',relloc(m)))
    disp(sprintf('Relative Position: %11.3f µm',position(m)))
end

%----------------------- End Image Processing Loop --------------------------
%Report image processing time
time = toc;
disp(['Image processed in ',num2str(time,'%9.3f'),' seconds'])
disp(' ')

%Report the total processing time for all images
endtime = clock;
disp(['Batch completed in ',num2str(etime(endtime,begtime),'%9.3f'),' seconds'])

%Recommend benchmark grayscale values
ublim = min([ubound(:,1:ne)],[],1); %Upper benchmark limit
lblast = max([lbound(:,1:ne)],[],1); %Lower benchmark limit
recbench = mean(middle,1); %Recommended benchmarks
%Keep the recommended benchmarks within limits if possible
for enum = 1:ne
    if ublim(enum) >= lblast(enum)
        recbench(enum) = min(max(mean(middle(:,enum)),lblast(enum)), ublim(enum));
    end
end

if diagnose
    disp('Choose benchmarks between these limits:')
    disp(sprintf('%10.3f',ublim))
    disp(sprintf('%10.3f',lblast))
    disp('Recommended benchmarks')
    disp(sprintf('%10.3f',recbench(1:ne)))
end
%---------------------------- Results ----------------------------------------

mnpos = mean(position);
sdpos = std(position);
disp(['Mean Position: ',num2str(mnpos,'%8.3f'),' µm'])
disp(['Standard Deviation: ',num2str(sdpos.*1E3,'%8.1f'),' nm'])

if saveresults
    save results imn regsize profile der edgloc relloc position mnpos sdpos
end

if brtcnt & (grayimage | savegrayimage)
    %Adjust the brightness and contrast of the grayscale image
    gryimg = (gryimg-dkavg)./(ltavg-dkavg).*scale+shift;
end

if savegrayimage
    imwrite(gryimg,'lastgrayimage.tif','tif')
end

%---------------------------- Plots ----------------------------------------

fig = 0;                %Figure number
if originalplot
    %Plot original profiles
    fig = fig+1;
    figure(fig); clf; set(fig,'Color','w')
    title('Original Grayscale Profiles')
    hold on
    for m = 1:nimg
        plot([1:npts]',orgprf(:,m),'-k')
    end
    hold off
    grid on
    xlim([0 npts])
end

if derivativeplot
    %Plot derivatives of profiles
    fig = fig+1;
    figure(fig); clf; set(fig,'Color','w')
    title('Derivatives of Grayscale Profiles')
    hold on
    for m = 1:nimg
        plot([1:npts]',der(:,m),'-k')
    end
    hold off
    grid on
    xlim([0 npts])
end

if grayimage
    %Display last grayscale image
    fig = fig+1;
    figure(fig); clf; set(fig,'Color','w')
    title('Cropped Grayscale Image')
    imshow(gryimg)
end

if profileplot
A.2.2 Post Processor for a Resolution Test

%NanoTran 3A Second Resolution Test Conducted 22 Jun 2004
%Neal Hubbard
%16 Mar 2005

%Parameters
ns = 5;                 %Number of steps
nm = 10;                %Number of measurements at each step
conf = .95;             %Confidence level
saveres = logical(1);   %Option to save results (0 or 1)

%Plot controls
HWR = .6;               %Height-to-width ratio
figwidth = 6;           %Width of figure on paper (inches)
axespos = [.075,.060,.910,.915]; %Position of axes (normalized units)
lnwd = 1;               %Line width for precision intervals (points)
export = logical(1);    %Option to export plots (0 or 1)
figres = 600;           %Resolution of printed figure (dpi)

%Input measurement data
load results_off
load results_on
%The files results_off and results_on are created by the image processor.
%They contain the following variables that are necessary for the execution
%of this program:
%mnoff                  %Average zero-current position
%position               %Position measurements made during the test
%Measured current (mA)
curr = [29.59; 29.59; 29.59; 29.59; 29.58; 29.58; 29.58; 29.58; 29.58; 29.58;
       29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75;
       29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75; 29.75;]
%Measured voltage (V)
2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 
2.539; 2.538; 2.538; 2.538; 2.539; 2.539; 2.539; 2.539; 2.539; 2.539; 
2.519; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 2.518; 
2.500; 2.500; 2.500; 2.500; 2.500; 2.500; 2.500; 2.500; 2.500; 2.500; 
2.499];

%Statistical analysis

% tnm = length(position); %Total number of measurements
dsp = position-mnoff; %Displacement (µm)
dspstep = reshape(dsp(1:nms),nm,ns); %Displacements grouped into steps
currstep = reshape(curr(1:nms),nm,ns); %Currents grouped into steps
voltstep = reshape(volt(1:nms),nm,ns); %Voltages grouped into steps
mnstep = mean(dspstep); %Mean displacement at each step
mncurr = mean(currstep); %Mean current at each step
mnvolt = mean(voltstep); %Mean voltage at each step
mnpower = mncurr.*mnvolt; %Mean power at each step

sdstep = std(dspstep); %Standard deviation of each step
pistep = tinv(.5+conf./2,nm-1).*sdstep; %Precision interval of each step

disp('Nanotran 3')
disp('Second Resolution Test Conducted 22 Jun 2004')
disp('Step   Displacement (nm)')
for i = 1:ns
    disp(sprintf('%3.0f %8.0f ±%4.0f',i,mnstep(i).*1E3,pistep(i).*1E3))
end

disp('Step   Current (mA)  Voltage (V)  Power (mW)')
for i = 1:ns
    disp(sprintf('%3.0f %10.2f %13.3f %12.2f',i,mncurr(i),mnvolt(i),mnpower(i)))
end

% Resolution

difstep = zeros(ns-1,1); %Absolute differences between sequential steps
clearance = zeros(ns-1,1); %Clearance between precision intervals
resstep = zeros(ns-1,1); %Resolved steps
difcurr = zeros(ns-1,1); %Difference in current between sequential steps

disp('Current Difference Between')
disp('Steps Increment (µA) tween Steps (nm) Precision Intervals (nm)')

nrs = 0; %Number of resolved steps
for i = 1:ns-1
    difstep(i) = abs(mnstep(i+1)-mnstep(i));
    %For a position increment to be resolved, it must be larger than the %sum of the position uncertainties of the two steps that define it.
    clearance(i) = difstep(i)-(pistep(i+1)+pistep(i));
    if clearance(i) >= 0
        nrs = nrs+1;
        resstep(nrs) = difstep(i);
    end
    difcurr(i) = abs(mncurr(i+1)-mncurr(i));
    disp(sprintf('%2.0f,%2.0f %6.0f%9s%6.0f%9s%9.0f',i,i+1,difcurr(i).*1E3,'',difstep(i).*1E3,'',clearance(i).*1E3))
end

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if nrs == 0
    res = NaN;
    disp('The resolution of the device is not defined.')
else
    res = mean(resstep(1:nrs)); %Resolution
    disp(['Resolution: ',num2str(res.*1E3,'%6.0f'),' nm'])
end

%Save results
if saveres
    save ResResults position mnoff dspstep mnstep currstep voltstep mncurr ...
    mnvolt mnpower sdstep pistep difstep difcurr resstep res
end

%Displacement steps with precision intervals
fig = 1;
figure(fig); clf
plotwidth = round(figwidth.*96); %Width of figure on screen (pixels)
plotsize = [plotwidth,round(HWR.*plotwidth)]; %Figure size on screen
plotpos = [1278,945]-plotsize; %Position of figure on screen (pixels)
figrestxt = ['-r',num2str(figres,'%4.0f')];
set(fig,'Position',[plotpos,plotsize],'Color','w','InvertHardCopy','off')
set(fig,'PaperPositionMode','auto')
hold on
plot(.5:1:nms,dsp(1:nms),'ko','MarkerSize',5)
for i = 1:ns
    text((.5+(i-1))./ns,-.030, ...        %Measurement number interval for the step
        ['Step ',num2str(i,'%2.0f')],'Units','normalized', ...
        'HorizontalAlignment','center','FontSize',9)
    stpint = [0,nm]+(i-1).*nm; %Measurement number interval for the step
    plot(stpint,mnstep(i).*ones(1,2),'k-', ...
        stpint,(mnstep(i)+pistep(i)).*ones(1,2),'k--', ...        %Number of tick marks and labels
        stpint,(mnstep(i)-pistep(i)).*ones(1,2),'k--','LineWidth',lnwd)
end
hold off
set(gca,'Position',axespos,'Color','none','Box','off','FontSize',9)
set(gca,'XLim',[0,nms],'XTick',[0:nm:nms],'XTickLabel','')
ylmt = [4.5,5.1];
ytck = [ylmt(1):1:ylmt(2)]; %Numbers for y-axis tick marks
nbl = length(ytck); %Number of tick marks and labels
ylbl = cell(1,nbl); %Labels for y-axis tick marks
for i = 1:nbl
    ylbl{i} = num2str(ytck(i),'%8.1f');
end
set(gca,'YLim',ylmt,'YTick',ytck,'YTickLabel',ylbl)
ylabel('Displacement (µm)')
if export
    %Export figure
    print('-dtiff',figrestxt,'NT3res_040622_2')
    set(fig,'Color','none')
    print('-dmeta',figrestxt,'NT3res_040622_2')
    set(fig,'Color','w')
end
A.2.3 Post Processor for a Repeatability Test

%NanoTran 3A Repeatability Test Conducted 22 Jun 2004
%Neal Hubbard
%3 Mar 2005

%Parameters
conf = .95; %Confidence level
firstbin = 4.45; %First bin location
binsize = .03; %Bin size
lastbin = 4.66; %Last bin location
saveres = logical(1); %Option to save results (0 or 1)

%Plot controls
HWR = .60; %Height-to-width ratio
figwidth = 4; %Width of printed figure (inches)
axespos = [.102,.155,.883,.805]; %Position of axes (normalized units)
export = logical(1); %Option to export plots (0 or 1)
figres = 600; %Resolution of printed figure (dpi)

%Load measurement data
load offresults
load onresults
%The files offresults and onresults are created by the image processor.
%They contain the following variables that are necessary for the execution
%of this program:
%meanoff %Average zero-current position
%onpos %Position measurements made during the test

%Measured current (mA)
current = [29.59; 29.58.*ones(28,1)];
%Measured voltage (V)
voltage = [2.501; 2.501; 2.501; 2.502; 2.501; 2.501; 2.501; 2.501;
2.501; 2.501; 2.501; 2.501; 2.501; 2.501; 2.501; 2.501;
2.502; 2.502; 2.502; 2.502; 2.502; 2.502; 2.502; 2.502;
2.502; 2.502];
power = current.*voltage;

%Statistical analysis
dsp = abs(onpos-meanoff); %Displacement
nrep = length(dsp); %Number of repetitions
meandsp = mean(dsp); %Mean displacement
sddsp = std(dsp); %Standard deviation of displacement
prec = tinv(.5+conf./2,nrep-1).*sddsp; %Precision interval
meancur = mean(current); %Mean current
meanvol = mean(voltage); %Mean voltage
meanpow = mean(power); %Mean power

%Report results
disp(' ')
disp('NanoTran 3')
disp('Repeatability Test Conducted 22 Jun 2004')
disp(sprintf('%-18s %8.0f','Repetitions',nrep))
disp(sprintf('%-18s %8.3f µm','Mean Displacement',meandsp))
disp(sprintf('%-18s %8.3f nm','Standard Deviation',sddsp.*1E3))
disp(sprintf('%-17s ±%8.3f nm','Repeatability',prec.*1E3))
disp(sprintf('%-18s %8.2f mA','Mean Current',meancur))
disp(sprintf('%-18s %8.3f V','Mean Voltage',meanvol))
disp(sprintf('%-18s %8.1f mW','Mean Power',meanpow))

%Save results
if saveres
    save RepResults dsp meandsp sddsp prec current voltage power meancur ...
    meandsp meanvol meanpow
end

%Histogram
fig = 2;                %Figure number
figure(fig); clf;
plotwidth = round(figwidth.*96); %Width of figure on screen (pixels)
plotsize = [plotwidth,round(HWR.*plotwidth)]; %Figure size on screen (pixels)
plotpos = [1278,945]-plotsize; %Position of figure on screen (pixels)
figrestxt = ['-r',num2str(figres,'%4.0f')];
set(fig,'Position',[plotpos,plotsize],'Color','w','InvertHardCopy','off')
hist(dsp,bins)
phan = findobj('Type','patch');
set(gca,'Position',axespos,'Color','none','Box','off','FontSize',9)
nlabels = length(bins);
binlabels = cell(nlabels,1);
for i = 1:nlabels
    binlabels{i} = sprintf('%4.2f',bins(i));
end
set(gca,'XLim',[firstbin-binsize,lastbin+binsize])
set(gca,'XTick',bins,'XTickLabel',binlabels)
xlabel('Displacement (µm)')
freqlimits = [0,12];    %Limits of the frequency axis
freqlabelinc = 2;       %Label spacing for the frequency axis
freqtickinc = 1;        %Tick mark spacing for the frequency axis
%Number of tick marks per label
freqtickperlabel = round(freqlabelinc./freqtickinc);
%Numbers for frequency axis tick marks
freqnums = [freqtickinc:frequickperlabel:freqlimits(2)];
nlabels = length(freqnums); %Temporary variable for array length
freqlabels = cell(1,nlabels); %Labels for frequency axis tick marks
for i = freqtickperlabel:frequickperlabel:nlabels
    freqlabels(i) = num2str(freqnums(i),'%2.0f');
end
set(gca,'YLim',freqlimits,'YTick',freqnums,'YTickLabel',freqlabels)
set(phan,'FaceColor',[.8,.8,.8],'FaceLighting','none')
ylabel('Frequency')
if export               %Export figure
    print('-dtiff',figrestxt,'NT3rep_040622')
    set(fig,'Color','none')
    print('-dmeta',figrestxt,'NT3rep_040622')
    set(fig,'Color','w')
end
A.2.4 Post Processor for a Hysteresis Test

%NanoTran 3A Hysteresis Tests Conducted 25 Jun 2004
%Neal Hubbard
%10 Mar 2005

%Parameters
ns = 10;                %Number of displacement steps from zero current to
the safe operating limit
saveres = logical(1);   %Option to save results (0 or 1)

%Plot controls
HWR = .6;               %Height-to-width ratio
figwidth = 6;           %Width of figure on paper (inches)
mkrcolor = [.5,.5,.5];  %Fill color for markers to denote forward motion
axespos = [.060,.105,.920,.870]; %Position of axes (normalized units)
export = logical(1);    %Option to export plot (0 or 1)
figres = 600;           %Resolution of printed figure (dpi)

%Input measurement data
load results_off
load results_1
load results_2
The files results_off, results_1, and results_2 are created by the image processor. They contain the following variables that are necessary for the execution of this program:
%offpos       %Average zero-current position
%pos1         %Position measurements made during the first test
%pos2         %Position measurements made during the second test

%Measured current (mA)
I1 = [0; 3.43; 6.70; 10.09; 13.46; 16.77; 20.15; 23.45; 26.81; 30.19; 33.5;
     30.2; 26.81; 23.45; 20.14; 16.77; 13.46; 10.08; 6.69; 3.42; 0];
I2 = [0; 15.78; 17.73; 19.69; 21.65; 23.72; 25.69; 27.62; 29.58; 31.54; 33.5;
     31.5; 29.6; 27.62; 25.69; 23.72; 21.65; 19.69; 17.73; 15.78; 0];

%Measured voltage (V)
V1 = [0; .274; .537; .810; 1.084; 1.357; 1.643; 1.929; 2.231; 2.556; 2.919;
     2.558; 2.231; 1.929; 1.643; 1.357; 1.084; .810; .536; .273; 0];
V2 = [0; 1.275; 1.438; 1.604; 1.774; 1.952; 2.129; 2.306; 2.496; 2.697;
     2.918; 2.698; 2.495; 2.307; 2.129; 1.952; 1.773; 1.604; 1.438; 1.275;
     0];

%Analysis
D1 = [offpos(1); pos1; offpos(2)]-mnoff; %Displacement from test 1
D2 = [offpos(2); pos2; offpos(3)]-mnoff; %Displacement from test 2
nmeas = length(D1);           %Total number of measurements in one test
revpt = (nmeas+1)./2;        %Index for the point of reversal
%Electrical power (mW)
P1 = I1.*V1;
P2 = I2.*V2;
%Electrical resistance (Ohm)
R1 = V1(2:nmeas-1)./I1(2:nmeas-1).*1E3;
R2 = V2(2:nmeas-1)./I2(2:nmeas-1).*1E3;
D1max = max(D1);             %Maximum displacement range
D2max = max(D2);             %Maximum displacement range
P1max = max(P1);             %Maximum electrical power
P2max = max(P2);             %Maximum electrical power
% Displacements grouped by step number and direction
D1step = [D1([2:ns]), D1([2.*ns:-1:ns+2])];
D2step = [D2([2:ns]), D2([2.*ns:-1:ns+2])];

% Power grouped by step number and direction
P1step = [P1([2:ns]), P1([2.*ns:-1:ns+2])];
P2step = [P2([2:ns]), P2([2.*ns:-1:ns+2])];

% Resistance grouped by step number and direction
R1step = [R1([1:ns-1]), R1([2.*ns-1:-1:ns+1])];
R2step = [R2([1:ns-1]), R2([2.*ns-1:-1:ns+1])];

% The first columns of D1step, D2step, P1step, P2step, R1step, and R2step
% contain displacements measured while moving in the forward direction; the
% second columns contain displacements measured while moving in the reverse
% direction. The steps (excluding the maximum displacement step) are indexed
% by row.
D1mnstep = mean(D1step, 2);
D2mnstep = mean(D2step, 2);
P1mnstep = mean(P1step, 2);
P2mnstep = mean(P2step, 2);

% Absolute hysteresis at each step
D1hys = abs(D1step(:, 2) - D1step(:, 1));
D2hys = abs(D2step(:, 2) - D2step(:, 1));

% Absolute hysteresis in power at each step
P1hys = abs(P1step(:, 2) - P1step(:, 1));
P2hys = abs(P2step(:, 2) - P2step(:, 1));

D1hysmax = max(D1hys);
D2hysmax = max(D2hys);
P1hysmax = max(P1hys);
P2hysmax = max(P2hys);

% Maximum relative hysteresis
D1hysrel = D1hysmax ./ D1max;
D2hysrel = D2hysmax ./ D2max;
P1hysrel = P1hysmax ./ P1max;
P2hysrel = P2hysmax ./ P2max;

% Find the ratio of displacement to power at each step
% Select only data with significant positive displacement
minlim = .010;  % Minimum significant displacement
masksig = Dstep > minlim;
masksig = masksig(:, 1) & masksig(:, 2);
% Ratio of displacement to power at each step in test 1
DPR1 = D1mnstep masked (masksig) ./ P1mnstep(masksig);
% Displacement hysteresis attributed to the power supply (µm)
pshys1 = P1hys(masksig) .* DPR1;
pshys1max = max (pshys1);
pshys1rel = pshys1max ./ D1max;
% Repeat for test 2
masksig = D2step > minlim;
masksig = masksig(:, 1) & masksig(:, 2);
% Ratio of displacement to power at each step in test 2
DPR2 = D2mnstep(masksig) ./ P2mnstep(masksig);
% Displacement hysteresis attributed to the power supply (µm)
pshys2 = P2hys(masksig) .* DPR2;
pshys2max = max (pshys2);
pshys2rel = pshys2max ./ D2max;

% Report results
disp(' ')}
disp('NanoTran 3')
disp('First Hysteresis Test')
disp(['The range is ',num2str(D1max,'%8.1f'),' µm.'])
disp(['The maximum power is ',num2str(P1max,'%8.1f'),' mW.'])
disp(['The maximum hysteresis is ',num2str(D1hysmax.*1E3,'%8.0f'), ... 
' nm or ',num2str(D1hysrel.*100,'%8.1f'),'% of full range.'])
disp(['The hysteresis in the power is ',num2str(P1hysmax.*1E3,'%8.0f'), ... 
' µW or ',num2str(P1hysrel.*100,'%8.2f'),'% of full range.'])
disp('')
disp('Second Hysteresis Test')
disp(['The range is ',num2str(D2max,'%8.1f'),' µm.'])
disp(['The maximum power is ',num2str(P2max,'%8.1f'),' mW.'])
disp(['The maximum hysteresis is ',num2str(D2hysmax.*1E3,'%8.0f'), ... 
' nm or ',num2str(D2hysrel.*100,'%8.1f'),'% of full range.'])
disp(['The hysteresis in the power is ',num2str(P2hysmax.*1E3,'%8.0f'), ... 
' µW or ',num2str(P2hysrel.*100,'%8.2f'),'% of full range.'])

%Save results
if saveres
    save HysResults I1 V1 P1 R1 D1 D1step P1step R1step D1max D1hys ... 
    D1hysmax D1hysrel D1hysrel P1hys P1hysmax P1hysrel I2 V2 P2 R2 D2 D2step ... 
    P2step R2step D2max D2hys D2hysmax D2hysrel P2hys P2hysmax P2hysrel
end

%Plot displacement v. current in both tests
fig = 3;                %Figure number
figure(fig); clf
plotwidth = round(figwidth.*96); %Width of figure on screen (pixels)
plotsize = [plotwidth,round(HWR.*plotwidth)]; %Figure size on screen
plotpos = [1278,945]-plotsize; %Position of figure on screen (pixels)
figrestxt = ['-r',num2str(figres,'%4.0f')];
set(fig,'Position',plotpos,'Color','w','InvertHardCopy','off')
set(fig,'PaperPositionMode','auto')
hold on
plot(I1(1:revpt),D1(1:revpt),'k^','MarkerSize',5,'MarkerFaceColor',mkrcolor)
plot(I1(revpt+1:nmeas),D1(revpt+1:nmeas),'k^','MarkerSize',5)
plot(I2(1:revpt),D2(1:revpt),'ko','MarkerSize',5,'MarkerFaceColor',mkrcolor)
plot(I2(revpt+1:nmeas),D2(revpt+1:nmeas),'ko','MarkerSize',5)
hold off
set(gca,'Position',axespos,'Color','none','Box','off','FontSize',9)
ylim = ylim; ylim(1) = 0; ylim(ylim)
xlabel('Current (mA)')
ylabel('Displacement (µm)')
legend('First Test, Forward Motion','First Test, Reverse Motion', ... 
    'Second Test, Forward Motion','Second Test, Reverse Motion',2)
legend('boxoff')
if export               %Export figure
    print('-dtiff',figrestxt,'NT3hys_040625')
    set(fig,'Color','none')
    print('-dmeta',figrestxt,'NT3hys_040625')
    set(fig,'Color','w')
end
A.2.5 Post Processor for a Drift Test

%NanoTran 3 Drift Test Conducted 25 Jun 2004
%Neal Hubbard
%3 Mar 2005

%Parameters
fiteq = logical(0);   %Option to fit equations to the data (0 or 1)
saveres = logical(1);   %Option to save results (0 or 1)

%Plot controls
HWR = .6;               %Height-to-width ratio
figwidth = 6;           %Width of figure on paper (inches)
axespos = [.070,.105,.910,.865]; %Position of axes (normalized units)
export = logical(1);   %Option to export plots (0 or 1)
figres = 600;           %Resolution of printed figure (dpi)

%Input test data
load testdata
%The file testdata is created by the image processor. It contains the
%following variables that are necessary for the execution of this program:
%mnoff                  %Average zero-current position
%position               %Position measurements made during the test

%Current (mA)
I = [32.50; 32.50; 32.50; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49; 32.49];
%Voltage (V)
V = [2.800; 2.800; 2.800; 2.800; 2.800; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799; 2.799];
%Input electrical power (mW)
P = I.*V;
time = [11 11 48; 11 13 07; 11 15 35; 11 16 48; 11 21 48; 11 31 48; 11 41 48; 11 51 48; 12 01 48; 12 11 48];
t = time(:,1).*60+time(:,2)+time(:,3)./60;
%Time from the begining of the test (minutes)
t = t-t(1);

%Analysis
d = (position(2:12)-position(2)).*1E3; %Absolute drift (nm)
mnoff = mean(position([1;13])); %Mean zero-current position (µm)
dsp = position(2:12)-mnoff; %Displacement (µm)
mndsp = mean(dsp); %Average displacement (µm)

%Report results
disp(' ')  
disp('NanoTran 3')  
disp('Drift Test Conducted 25 Jun 2004')  
disp(['The total drift over ',num2str(tt,'%4.0f'),' minutes is ', ...  
     num2str(td,'%8.2f'),', nm.'])  
disp(['The average rate of drift is ',num2str(rate,'%8.2f'),' nm/hour.'])

if fiteq
% Least-squares linear fit to drift
c = [ones(nm,1),t]; % Coefficients of the linear equation
slope = c(2).*60; % Slope of the line (nm/hour)
fitt = [0:t(end)]';
linfitd = c(1)+c(2).*fitt;
disp(' ')
disp('Linear Fit')
disp(['The slope of the line is ',num2str(slope,'%8.2f'),' nm/hour.'])

% Least-squares exponential fit to drift
% The equation is d = A.*(1-exp(-1.*t./tau)). A is the amplitude; tau is % the time constant. The Curve Fitting toolbox provides functions for % finding the coefficients A and tau.
model = fittype('A*(1-exp(-1*t/tau))','independent','t');
fitopt = fitoptions('Method','NonlinearLeastSquares', ...
    'StartPoint',[25,9]);
[expfit,fitstat,fitdetail] = fit(t,d,model,fitopt);
expfitt = feval(expfit,fitt);
disp(' ')
disp('Exponential Fit')
disp(expfitt)
disp('     Fit Quality Statistics:')
disp(fitstat)
disp('     Detailed Output from the Solver:')
disp(fitdetail)
end

% Save results
if saveres
    save DftResults dsp d t P tt td rate
end

% Drift v. Time
fig = 4; % Figure number
figure(fig); clf
plotwidth = round(figwidth.*96); % Width of figure on screen (pixels)
plotsize = [plotwidth,round(HWR.*plotwidth)]; % Figure size on screen
plotpos = [1278,945]-plotsize; % Position of figure on screen (pixels)
figrestxt = ['-r',num2str(figres,'%4.0f')];
set(fig,'Position',plotpos,'Color','w','InvertHardCopy','off')
set(fig,'PaperPositionMode','auto')
hold on
plot(t,d,'ko','MarkerSize',5)
if fiteq
    plot(fitt,linfitd,'k--')
    plot(fitt,expfitt,'k-')
end
hold off
set(gca,'Position',axespos,'Color','none','Box','off','FontSize',9)
xlmt = [0,t(nm)]; % X axis limits
xtck = [0:10:t(nm)]; % X axis tick mark locations
nlab = length(xtck); % Temporary variable for array length
xlab = cell(nlab,1); % X axis labels
for i = 1:nlab
    xlab(i) = num2str(xtck(i),'%2.0f');
end
set(gca,'XLim',xlmt,'XTick',xtck,'XTickLabel',xlab)
xlabel('Time (minutes)')
ylabel('Drift (nm)')
if fiteq
    legend('Measured Data','Linear Fit','Exponential Fit',0)
    legend('boxoff')
end
if export               %Export figure
    print('-dtiff',figrestxt,'NT3dft_040625')
    set(fig,'Color','none')
    print('-dmeta',figrestxt,'NT3dft_040625')
    set(fig,'Color','w')
end
A series of tests are introduced in Chapter 5 to measure the resolution, repeatability, hysteresis, and drift of a nanopositioner. Definitions and theoretical considerations are discussed there. The specific procedures outlined here clarify the manner in which the tests are performed. The details may be useful for verifying the statistical significance of the results, duplicating the tests, and devising new methods of characterizing the accuracy of a nanopositioner.

The MEMS chip was released as described in Section 2.4, but before the nanopositioners could be tested in the SEM the chip had to be mounted on a sample holder and electrical connections had to be made. The chip was placed on a piece of carbon tape in a ceramic chip carrier. Gold wires with a diameter of 38 µm were fused to the bond pads on the chip and to gold-plated leads on the chip carrier. The chip carrier plugged into a base that was mounted on a fiberglass wafer board; the carrier could be removed from the base without disturbing the gold wires, so the chip could easily be exchanged. The board was attached to an aluminum block that was designed to fit on the sample stage in the SEM. The electrical interface on the SEM plugged into the board; it provided electrical connec-
tions between the nanopositioners and the power supply, which was located outside the SEM. Figure B.1 shows the sample holder in the SEM; it holds two MEMS chips.

Several steps were taken to prevent the accumulation of electrostatic charge in the polysilicon and silicon-nitride layers. One of the leads on the chip carrier was reserved as a ground path for the electron beam. The pin on the base that corresponded to this lead was connected to the aluminum block and, hence, to the sample stage. Blankets of polysilicon served as conductive backgrounds for the SEM images (Section 3.3). Some of the polysilicon blankets were connected directly to the SEM ground lead with gold wires; others were connected to the substrate. The surface of the chip carrier to which the chip was mounted was plated with gold; this surface was also connected to the SEM ground lead. Carbon tape is conductive, so the silicon substrate was grounded. These sample preparation steps resulted in sharper images and less image drift.
B.1 Resolution

To determine the size of the current increment for the resolution test, estimate the resolution of the nanopositioner. A convenient approximation is the width of the 95% precision interval obtained in a repeatability test. Convert this to a current increment by dividing by the displacement-to-current sensitivity of the nanopositioner at the middle of its range. Compare the calculated current increment to the resolution of the power supply and use the larger increment first. Test the resolution of the nanopositioner with this increment as well as one larger and one smaller. A current-divider circuit may be necessary to decrease the resolution of the power supply.

The resolution test proceeds as follows:

1. Measure the position at zero input current ($p_{0,1}$).

2. Turn up the current monotonically to the value that results in a displacement equal to half the range. This is the mid-range current. Measure the position ten times ($p_{1,j}|_{j=0...9}$). Record the time, current, and voltage at the beginning of each measurement. If the zero-current and mid-range positions are not both visible at the desired magnification, record the mid-range displacement at a lower magnification and take images at the higher magnification to measure the random position error.

3. Increase the current by the desired increment two times. Measure the position ten times at each step ($p_{i,j}|_{j=2,3,j=0...9}$). Record the time, current, and voltage at the beginning of each measurement. If desired, the current may be increased beyond the mid-range value by the desired increment six times. In this manner, tests with steps one, two,
and three times the size of the nominal step are accomplished simultaneously with fewer images, and the three tests have at least two steps each.

4. Decrease the current by the same increment to the mid-range value. Measure the position 10 times at each step \( (p_{i,j})|_{i=4,5; j=0...9} \). Record the time, current, and voltage at the beginning of each measurement.

5. Set the current to zero and measure the position once \( (p_{0,2}) \).

Compute the mean, \( \mu_i \), and standard deviation, \( \sigma_i \), at each step \( (i = 1...5) \). The 95% precision interval at each step is

\[
\mu_i \pm \varepsilon_i \quad \text{(B.1)}
\]

where

\[
\varepsilon_i = t_{\nu, P} \sigma_i \quad \text{(B.2)}
\]

is the width of the precision interval. The \( t \) estimator, \( t_{\nu, P} \), is obtained from the Student’s \( t \) distribution \([113,114]\); the number of degrees of freedom, \( \nu \), is one less than the number of repetitions in the test, and \( P \) is the probability (95%). The size of each step is

\[
s_i = |\mu_i - \mu_{i-1}| \quad \text{(B.3)}
\]

The criterion for a step to be resolved is

\[
s_i - (\varepsilon_i + \varepsilon_{i-1}) \geq 0 \quad \text{(B.4)}
\]

Average the sizes of the steps for which the above criterion holds to obtain the resolution.

Plot the displacement against time to illustrate the test; the mean displacement and precision interval of each step may also be plotted. Observe trends in the measurements at each step as well as hysteresis between the up-scale and down-scale steps.
B.2 Repeatability

1. Measure the position with zero input current \((p_{\text{off},1})\).

2. Set the current source to the value that results in a displacement equal to half the range. Turn on the current and measure the position \((p_{\text{on},1})\). Record the time, current, and voltage at the beginning of the image scan. If the zero-current and mid-range positions are not both visible in the field of view, record the nominal mid-range displacement at the smaller magnification and make more accurate measurements with only the closest reference object in view.

3. Turn off the current and wait about 1 s.

4. Repeat steps 2 and 3 for a total of 31 repetitions. The position measured at each repetition is \(p_{\text{on},i}\). Record the time, current, and voltage at the beginning of each measurement. If the zero-current position is within the field of view, measure it after cycles 10 and 20 \((p_{\text{off},11}, p_{\text{off},21})\).

5. Measure the zero-current position at the end of the test \((p_{\text{off},32})\).

Compute the mean zero-current position, \(\mu_{\text{off}}\). Note whether the zero-current measurements, \(p_{\text{off},i}\), are within measurement uncertainty about \(\mu_{\text{off}}\). If so, the zero-current position may be assumed to remain constant throughout the test. If not, the actuators are probably over-heating.

The displacement at each repetition is

\[
d_i = p_{\text{on},i} - \mu_{\text{off}}
\]  

(B.5)
Compute the mean, \( \mu \), and standard deviation, \( \sigma \), of the displacements. The 95% precision interval is

\[
\mu \pm \varepsilon 
\]

where

\[
\varepsilon = t_{\nu, p} \sigma 
\]

is the width of the precision interval based on the Student’s \( t \) distribution. The repeatability is \( \pm \varepsilon \). If the repeatability is about twice the measurement uncertainty, then the measurement process is accurate enough.

Trends in displacement and power may be correlated. Plot displacement against power. It may be helpful to compute the 95% precision interval of the power and relate it to the position repeatability by multiplying by the sensitivity of displacement to power (the ratio of the means). If power is more repeatable than displacement, friction is probably impeding the motion of the nanopositioner.

**B.3 Hysteresis**

1. Measure the position with zero input current \( (p_{1,0}) \).

2. Turn up the current monotonically in increments equal to one tenth of the safe operating limit. Measure the position at each step in the forward direction \( (p_{1,1}, r, \ldots, p_{1,9}, r, p_{1,10}) \). Record the time, current, and voltage at the beginning of each measurement.

3. Decrease the current monotonically, stopping at the same values at which the forward positions were measured. Measure the position at each step in the reverse direc-
tion \((p_{1,9,r}, \ldots, p_{1,1,r})\). Record the time, current, and voltage at the beginning of each measurement.

4. Repeat steps 1–3 for a total of 41 position measurements \((p_{2,0,1}, p_{2,1,r}, \ldots, p_{2,9,r}, p_{2,10}, p_{2,9,r}, \ldots, p_{2,1,r}, p_{3,0})\).

Compute the hysteresis at each current in both tests, \(h_{i,j} \bigg|_{i=1,2;} j=1\ldots9\), as

\[
h_{i,j} = |p_{i,j,r} - p_{i,j,f}| \tag{B.8}
\]

The hysteresis of the nanopositioner is

\[
H = \frac{\max(h_{i,j})}{\max(p_{i,10})} \cdot 100\% \tag{B.9}
\]

The zero-current positions, \(p_{i,0} \bigg|_{i=1\ldots3}\), are averaged to obtain \(\mu_{\text{off}}\). The displacement measurements are

\[
d_{i,j,f} = p_{i,j,f} - \mu_{\text{off}}
\]
\[
d_{i,j,r} = p_{i,j,r} - \mu_{\text{off}}
\]
\[
d_{i,10} = p_{i,10} - \mu_{\text{off}} \tag{B.10}
\]

for \(i = 1,2\) and \(j = 1\ldots9\). The nanopositioner is calibrated from the plot of displacement versus current. The maximum range of the nanopositioner is

\[
R = \max(d_{i,10}) \tag{B.11}
\]
B.4 Drift

The drift test must be performed when the device has been at room temperature for a period of several hours. It is helpful to determine the safe operating limit prior to the day of the drift test.

The test proceeds as follows:

1. Measure the position with zero input current ($p_0$).

2. Turn on the current to the safe operating limit. Measure the position ($p_1$), start the timer, and record the current and voltage. Measure the position four more times in immediate succession ($p_2, \ldots, p_5$) recording the time, current, and voltage at the beginning of each measurement.

3. Measure the position at time 10:00 and every 10 minutes thereafter, up to at least time 60:00 ($p_{6}, \ldots, p_{11}$). Record the time, current, and voltage at the beginning of each measurement. Blank the electron beam between measurements to prevent the accumulation of electrical charge, which may cause the image to drift. Continue the test beyond 60 minutes if the current and voltage have not yet settled.

4. Measure the zero-current position at the end of the test ($p_{12}$).

The absolute drift of the nanopositioner at each time, $d_i|_{i=1, \ldots, 11}$, is given by

$$d_i = p_i - p_1$$  \hspace{1cm} (B.12)

Plot drift versus time. Fit a negative exponential curve to the drift measurements. The equation has the form
where $A$ is the steady-state drift and $\tau$ is the time constant. If the fit is good, consider heat transfer as a possible cause of the drift. Report the absolute drift at the end of the test. The change in the zero-current position may also be of interest.