A Scanner Design for Microscopy Applications

He heaved his monumentally vile body round in his ill-fitting, slimy seat and stared at the monitor screen on which the starship *Heart of Gold* was being systematically scanned.

(Douglas Adams, The Restaurant at the End of the Universe)

A.1 Piezoelectric Scanners

A.1.1 The Piezoelectric Effect

In crystalline dielectrics that lack inversion symmetry, such as quartz or tourmaline, mechanical stress along certain crystal axes causes the unit cell to become polarized as the charged atoms forming its basis move relative to each other. The direct piezoelectric[1] effect was discovered by Pierre and Jacques Curie in 1880. The polarization of the material is a linear function of the stress and in the absence of an external electrical field is given by

$$P_i = d_{ijk}\sigma_{jk}, \tag{A.1}$$

where P_i is the polarization vector, σ_{jk} is the mechanical stress, d_{ijk} is called the piezoelectric strain tensor, and the Einstein summation convention has been used [1]. As a third-rank tensor, d_{ijk} has 27 components, but since the stress tensor σ_{jk} is symmetric no more than 18 of them are independent.[2]

[1] from Greek πιέζειν, 'to squeeze'

[2] In engineering texts, j and k are sometimes contracted into a single index that runs over the 6 independent components of the strain tensor. This is known as Voigt's notation.

Conversely, an external electric field changes the equilibrium configuration of the basis atoms and leads to a deformation of the crystal, which is described by another linear relation:

$$\varepsilon_{jk} = d_{ijk} E_i, \tag{A.2}$$

where ε_{jk} is the strain tensor, E_i is the electric field vector, and the material is assumed to be relaxed. The converse piezoelectric effect constitutes the underlying principle of piezoelectric actuators [1].

A.1.2 Ferroelectric Ceramics

Actuators are most commonly assembled from ferroelectric ceramics such as lead zirconate titanate (PZT, $Pb(Zr_xTi_{1-x})O_3$). Ferroelectric materials are piezoelectric materials that spontaneously polarize below the Curie temperature T_C because of symmetry breaking and can produce a strong piezoelectric response even as a polycrystal since the orientation of the polarization can be changed externally. The individual pieces of ceramic are produced by pressing a precursor powder in the desired shape and sintering the workpiece. The resulting actuator is polycrystalline with randomly oriented grains and polarization domains and has initially almost no ability to expand or contract. In order to polarize the ceramic, the pieces are heated above T_C and cooled down in the presence of a strong electric field. After this process, the polarization direction in the grains mostly coincides with the equivalent crystal axis that is best aligned to the external field [1].

A.1.3 Deviations from Linearity

Although the piezoelectric effect, Eq. (A.2), is linear in nature, practical actuators exhibit a certain degree of nonlinearity [2–5]: For ferroelectric ceramics, the piezoelectric strain tensor depends on the average remnant polarization, which can change with time or in response to an external electric field. The effect is small for low driving voltages and small extensions and is consequently of limited importance to atomic scale imaging, which was the initial focus of SPM. Metrology and lithography applications, however, require accurate calibration and repeatability over a large scanning area and hence are critically affected by nonlinearity and drift [2, 3].

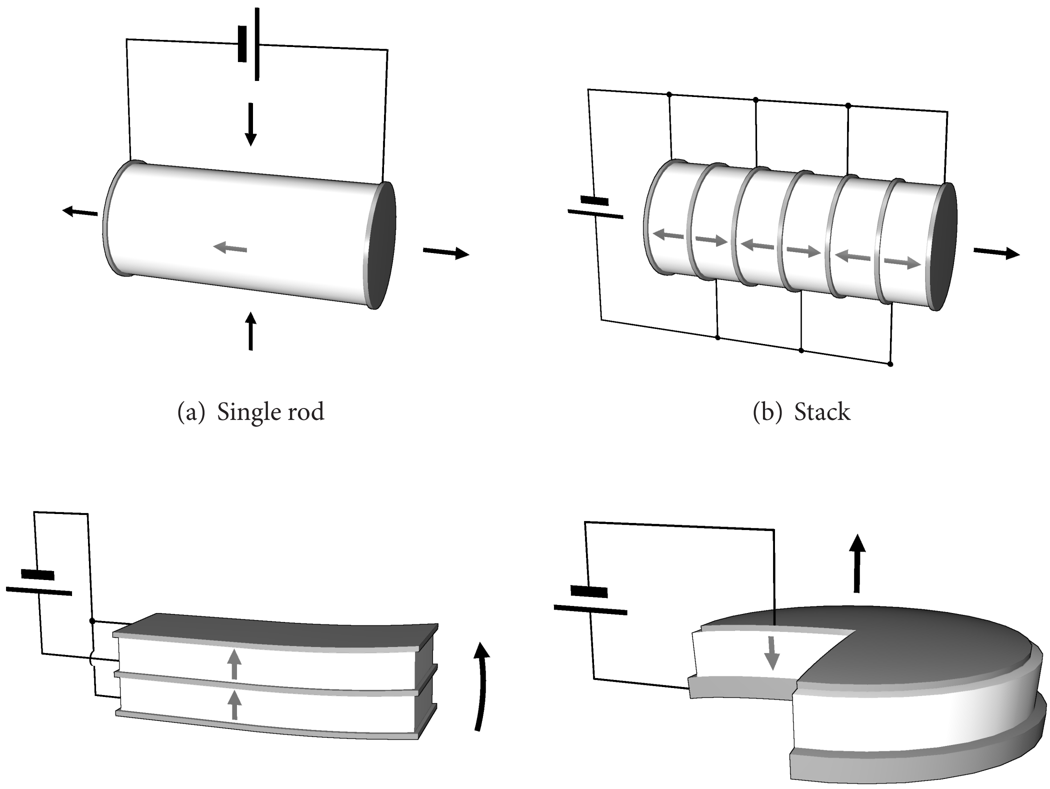
As the strength of the piezoelectric response is affected by the external electric field, the strain depends on the speed and direction of the change in the driving voltage. Accordingly, the relation between input voltage and displacement exhibits hysteresis. In typical ferroelectric actuators the error caused by hysteresis is 5 % to 10 % of the extension [4].

Even in a constant electric field the extension of the ferroelectric material initially continues to change slowly, an effect which is known as 'creep' or 'drift'. It is caused by the movement of the walls between individual polarization domains, which results in a change of the average polarization.

Over the lifetime of an actuator the alignment created by the poling process may degrade. This is especially true if the piezoceramic is heated to temperatures close to T_C, exposed to high electric fields in the direction opposite to its polarization, or used only rarely. Conversely, regular use of the actuator prevents degradation and can actually improve the alignment.

A.1.4 Basic Actuators

In the presence of an external electric field parallel to its average polarization, a rod of ferroelectric material will expand along the polarization axis and contract in the direction normal to it, as shown in Fig. A.1(a). If the electric field is reversed, the rod will contract along the poling axis and expand in the perpendicular direction. A rod of this kind can be used as a simple one-dimensional actuator, the range of which is proportional to its length and the range of the electric field. The field strength in the poling direction is limited by dielectric breakdown, while the allowable field strength in the inverse direction is typically much lower and given by the onset of depoling. The field required to achieve the theoretical maximal extension of a rod of commercially available PZT is several kV/mm, which makes this design



(a) Single rod
(b) Stack
(c) Bimorph
(d) Unimorph disk

Figure A.1: Basic piezoelectric actuators made from ferroelectric ceramic. Grey arrows indicate average polarization. Black arrows show deformation or movement.

impractical for many applications. Instead, the arrangement shown in Fig. A.1(b) is commonly used. Here the rod is replaced by a stack of thin piezoelectric disks with alternating poling connected in parallel. The voltage required to reach full extension is divided by the number of disks.

The deformation normal to the direction of the electric field can also be exploited in piezoelectric actuators. In Fig. A.1(c) two layers of ferroelectric material are combined in an arrangement similar to a bimetallic strip. Application of an external voltage causes one of the layers to expand while the other contracts so that the device bends upwards. If one end is clamped, the other will move in an arc by a distance much larger than the deformation of the ceramic. In general, a stacked structure comprising an arbitrary number of piezoelectric and elastic layers is known as a multimorph, which makes the structure in Fig. A.1(c) a bimorph. A familiar application of this idea—frequently used as a transducer or loudspeaker—is the unimorph[3] disk shown in Fig. A.1(d) consisting of just one piezoelectric layer attached to an elastic metal base, which doubles as one of the contacts. If a voltage is applied, the disk buckles axially.

A.1.5 Scanner Design

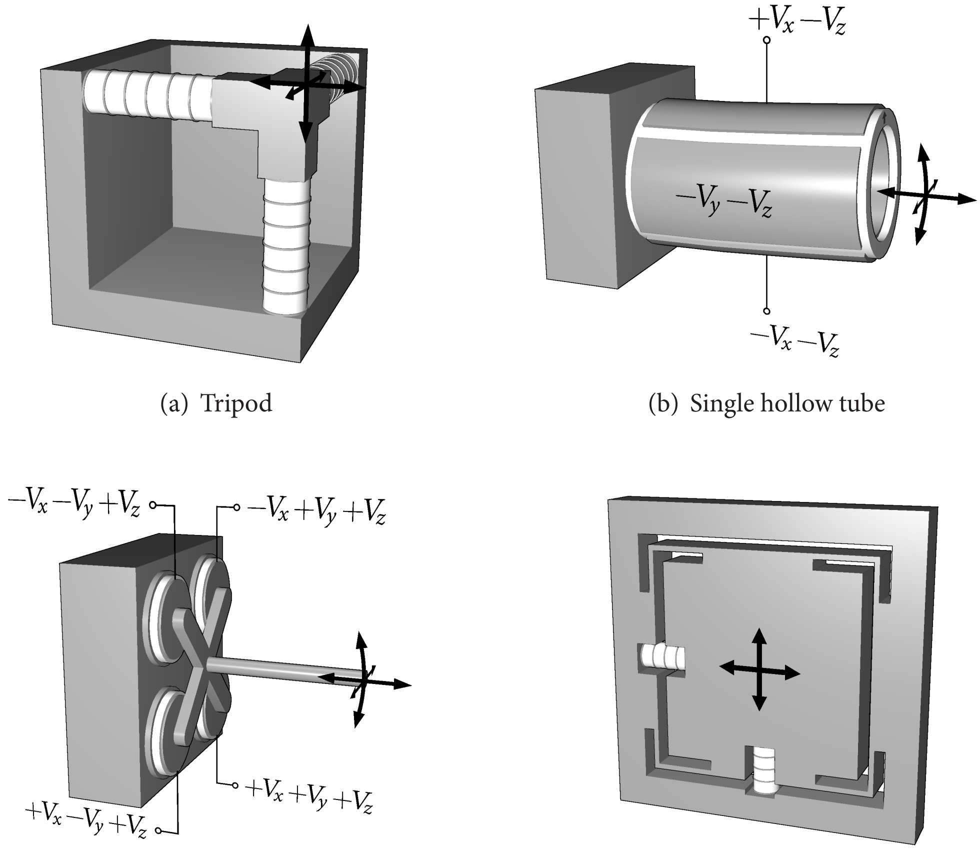
Tripod

Fig. A.2(a) shows the most straightforward three-dimensional scanner geometry, which was used by Binnig *et al.* [6] in the earliest SPM experiments. A separate one-dimensional piezoelectric actuator—typically a standard PZT stack—is used for each axis of movement. Since the position on the individual axes can be controlled independently, the feedback and data acquisition modules can be kept simple. Even so, because of the geometrical coupling of the actuators cross talk of the order 0·1 % to 1 % between the axes is present and may need to be corrected for [7]. The disadvantage of this design is an increased mechanical complexity and a limited range of movement in the plane of the sample.

Single Hollow Tube

In 1986 Binnig *et al.* introduced a sophisticated scanner, which requires only one piece of piezoelectric material [8,9]. The design makes use of the transverse component of the piezoelectric response and is now used in the majority of new SPMs. As illustrated in Fig. A.2(b), the piezoceramic is formed as a hollow tube with a single contact on the inside as well as four contacts on the outer surface, where each covers a quarter of the circumference. By applying equal and opposite voltages V_x (V_y) to opposing quadrants of the tube, the sides

[3] Rather confusingly, the similar term 'monomorph' is sometimes used to describe a different actuator lacking the elastic layer. Buckling is then induced by an inhomogeneous field.



(a) Tripod (b) Single hollow tube

(c) Lever (d) Two-dimensional flexure stage

Figure A.2: Piezoelectric SPM scanners. Arrows indicate scanner movement.

are induced to contract and expand respectively, and the tube bends. At the same time, a bias voltage V_z applied to all four quadrants with respect to the central contact changes the length of the entire tube. If one end of the tube is clamped to the support of the instrument, the other end, which may hold either the sample or the probe, can scan a three-dimensional volume [8,10]. The range of sideways movement that can be achieved in this manner is much larger than the longitudinal expansion of the sides of the hollow tube. The drawback is that the movement in the (x, y)-plane and along the z-axis is no longer independent. The interference between the three axes is much larger than with the tripod geometry: The free end of the tube maps out a curved surface if V_z is kept constant. Moreover, a complex controller module is required to translate (x, y, z)-values into voltages.

Lever Design

Fig. A.2(c) shows a design proposed by Mariani *et al.* [11] that is conceptually similar to the tube scanner but does not require a specialized piece of piezoceramic. Instead, four standard unimorph disk actuators are laid out in the corners of a square and connected by a rigid cross supporting a lever. If the actuators on one side of the square retract while the ones on the other side move upwards the lever swings to that side. Movement along the lever axis—with a limited range given by the travel of the disks—can be achieved by driving all four actuators in parallel. The design suffers from the same cross talk problems as the tube scanner and a lessened stiffness, but can be implemented very cheaply and allows for potentially very large backlash-free amplification of the movement in the (x, y)-plane (at the expense of reduced stiffness) [11]. A further simplification uses a single disk divided into four quadrants instead of four separate actuators.

Flexure Stages

Conventional three-dimensional scanners are not only afflicted by cross talk, but take up space directly above or below the point where the probe comes in contact with the sample, making it difficult to integrate the SPM with other microscopy techniques. This is particularly problematic for near field optical microscopy. Several schemes have been proposed to move the scanner hardware away from the optical axis and contain it in a flat package [12]. A design that uses a set of leaf springs and levers to transmits the movement of an off-axis actuator to the sample stage as illustrated in Fig A.2(d) has proven particularly useful. The entire device is machined from a single piece of metal, and hinges are provided by the flexure of thin metal bridges, avoiding backlash and the need for lubrication [5, 13]. Geometrical amplification of the movement range is possible by a suitable arrangement of levers as in the original design by Scire [13], but reduces the stiffness of the translator [7]. It is possible to combine several independent stages, although the combination of x and y scanners in a single frame as shown in Fig. A.2(d) helps minimizing Abbe errors [13].

A.2 Electromagnetic Scanners

A.2.1 Electrodynamic Actuators

In an electrodynamic or inductive actuator a solenoid carrying the driving current moves in the radial field between the poles of a permanent magnet. The solenoid experiences a force, which is balanced by a diaphragm or spring, so that the displacement of the actuator is

$$d = \frac{F}{k} = \frac{nI\Phi}{k}, \tag{A.3}$$

where F is the force, k the spring constant, n the number of windings in the solenoid, I the current, and Φ the magnetic flux in the gap.

This arrangement, often know as a voice coil, is familiar from acoustic loudspeakers and used to see widespread use in the laboratory for micropositioning applications. Despite the fact that electrodynamic actuators are virtually free from hysteresis and drift and do not require high voltage electronics, they have been superseded by piezoelectric elements for fine positioning [14]. In conventional voice coil designs a moderate current causes a large displacement and the device has a low resonant frequency. Nanometre resolution would require a sensitive current control that is impossible to achieve in practice and the actuator position is highly susceptible to acoustic and electromagnetic noise on this length scale.

Binnig *et al.* [15] have shown that these disadvantages may be overcome by increasing the spring constant that the solenoid pushes against to such an extent that the travel for conveniently controllable driving currents is reduced to the desired scanner range. The deviations caused by instabilities in the driving current are demagnified proportionally so that the need for sensitive electronic control is obviated. At the same time, the effective stiffness of the scanner is increased, leading to higher mechanical resonance frequencies and reducing the interference from the scanning frequency and low frequency acoustic noise.

A.2.2 Scanner Design

Electrodynamic actuators can be used to construct a three-dimensional scanner in much the same way as piezoelectric actuators. While there is no analogy to the the hollow tube design of Fig. A.2(b), the other scanners shown in Fig. A.2, which use individual one-dimensional positioners, can be implemented readily. Most commercial offerings use a form of flexure stage, while MARIANI has realized a variant of his inexpensive lever scheme that employs standard voice coils [14]. BINNIG *et al.* [15] have used a central lever that doubles as the elastic load for both x and y actuators.

Unlike piezoelectric scanners, electromagnetic devices can deliver large travel ranges even with small actuator sizes. This makes them the preferred solution for applications where miniaturization is important, for example where a large number of probes is to be operated independently within a limited area [16].

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