Piezoelectric Micromanipulators

Electrically operated micromanipulators add automatic high-speed movement to normal manual control.

Gordon W. Ellis

In the study of living cells biologists have not been content with mere visual observation. They have poked and prodded the cell and have rearranged its parts. Microdissection experiments have involved incisions, amputations, injections, and transplantations.

The dimensions of most cells are too small for the movements required for surgery at the cellular level to be performed directly by hand. Use of a machine is necessary to translate hand movements into the desired micromovements of tools. In early micromanipulators this objective was accomplished through moving screws or levers to produce small movements of a microtool. With these machines the movement of the operator's hand was not simply related to the resulting tool movement—for example, rotating a knob resulted in a translation of the tool. For movements not on the principal mechanical axes of the machine, simultaneous rotation of as many as three knobs was required to produce diagonal movement of the tool. With such systems, learning to perform relatively complex micrurgy required a great deal of time and talent on the part of the operator. Early in the 1930's Emerson (*1*) developed a mechanical, and de Fonbrune (*2*) developed a pneumatic, micromanipulator whose tool motion, as seen through the microscope, was directly related, in the horizontal plane, to the movement of a control handle. Since that time a number of micromanipulators have been devised which employ similar relationships between control and tool movement. Cailloux (*3*) developed a hydraulic micromanipulator (subsequently offered commercially in a pneumatic form) which provided a direct relationship between control handle movement and tool movement in all directions.

The microworld, as seen at high magnification under the microscope, is a peculiar space having breadth and width but only negligible depth. For this reason it seems unnecessary to include all three dimensions in a direct relationship to tool movement because displacement of the tool along the optical axis quickly results in disappearance of the tool from the field of view. Since visual movement through this microworld is achieved by rotating the fine-focus knob of the microscope, it seems reasonable to achieve vertical movement of the tool by rotating a control knob. This is the procedure employed in several of the currently popular micromanipulators. Most of these instruments have means for varying the reduction ratio between hand and tool movement. This is an important feature, since for greatest ease of operation the movement of the control handle should correspond in magnitude as well as direction to the movement of the tool image.

If we disregard such problems as drift, lag, and extraneous vibration of the microtool, it appears that several micromanipulators satisfy the major requirements for successful positioning of a microtool with a minimum of learning time required of the operator.

We have so far considered essentially static problems and have ignored the dynamic problems encountered in an actual micrurgical operation. One important dynamic problem can be illustrated by the following example. To insert a salt-bridge microelectrode or micropipet into the cytoplasm of a living cell requires the passage of a relatively blunt object through the thin and highly extensible cell membrane. To place the tool in contact with the cytoplasm requires the rupture of this membrane. Rupture of the membrane requires application of a load that will cause mechanical failure of the membrane structure. If the load is applied slowly, the membrane will be extended along the microtool until the stress in the membrane exceeds its breaking strength. During elongation of the membrane, stress is relieved by flow in the membrane. Since flow is opposed by viscous drag and the extent to which this stress is relieved is time-dependent, it follows that the elongation occurring before rupture stress is reached is velocity-dependent. The higher the tool velocity the smaller the membrane elongation before rupture. That this is a real problem in micrurgical work has been shown by the experiences of several investigators. Mitchison (*4*) has published a photomicrograph showing the enormous extensibility of the membrane of the sea urchin egg, and Tyler and Monroy (*5*) have published an account of the difficulty they experienced in placing a micropipet or microelectrode in real contact with the cytoplasm of echinoderm eggs. Tyler and Monroy found that a blow to the table supporting the apparatus would jar the microtool and puncture the membrane. Pascoe (*6*) found that a ganglion capsule that resisted penetration to the point of breaking the microelectrode could be readily penetrated with the aid of a rapid thrust of the microelectrode delivered by means of a piezoelectric transducer.

These observations illustrate an important lack in the capabilities of currently available micromanipulators. Except in the case of Pascoe's piezoelectrically driven microtool, little attention has been given to the velocity of microtool movement. At best these machines can accomplish changes in tool position as rapidly as the operator can move the control handle. However, the velocity attained by the microtool is, at the reduction ratios used at high magnification, one thousandth part or less of the velocity of the operator's hand. This is, of course, a natural consequence of the movement reduction achieved by the micromanipulator—the movement reduction which is its primary reason for existence—and cannot be avoided with conventional systems.

The solution of this problem requires a new approach to micromanipulator design, wherein the velocity, as well as the accuracy and magnitude of the tool movement, is considered.

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A New Approach to Micromanipulator Design

A first step in the design of any instrument is a statement of the requirements the instrument is to satisfy. In this case the first requirement is to move the microtool in a controlled fashion at speeds much higher than could be achieved by hand motion. For maximum versatility, high-speed movement should be possible in any direction in which the microtool could be moved manually at normal speeds. As these movements are to take place more rapidly than the operator can move his hand, it follows that the operator will not be able to direct these motions as they occur. Therefore, the instrument must include some means for predetermining these movements with respect to velocity, amplitude, and direction so that they may be initiated at the will of the operator, then performed according to a preset program.

As a second requirement, the new micromanipulator should perform as well under manual control as the best machines currently available. In my opinion this requirement is no less important than the first.

The final requirement is for simplicity of design. If possible, the machine should be designed in such a way that the quality of its performance is inherent in the design rather than dependent on exceedingly precise construction.

High-velocity movements must originate with driving movements initially of the correct magnitude, since the introduction of a movement-reduction mechanism between the source of the microtool driving force and the microtool results in a reduction in movement velocity. All of the currently employed micromanipulators, except for the Bush, Duryee, and Hastings (*7*) electrothermal micromanipulator, derive the motive force for microtool movement from the motion of the operator's hand. In the Bush, Duryee, and Hastings micromanipulator, movement of the microtool originates in the thermal expansion of fine wires. This movement is transmitted directly to the microtool. In essence this machine consists of a modulator that uses hand position to regulate the flow of electrical energy to a transducer that ultimately converts electrical energy to mechanical movement. There are, of course, many ways in which the flow of electrical energy can be modulated in a precise manner at very high speeds. The number of electromechanical transducers that can follow rapid changes in an electrical signal is more limited. The electrothermomechanical transducer of the Bush, Duryee, and Hastings machine, having a time constant of about 1 second, is not one of these. Only two categories of currently employed electromechanical transducers are worth considering in this context. These are the magnetostrictive and the piezoelectric types. In addition to moving at high velocity, both types can move slowly and sustain the static deflections required for manual control. The use of a single microtool movement mechanism for both the high-speed automatic movements and the manually controlled motions helps promote the desired simplicity of design.

Comparison of magnetostrictive and piezoelectric transducers shows that the maximum static strain possible with magnetostriction is less by about an order of magnitude than that obtainable piezoelectrically (*8*). This means that, for equal performance as a micromanipulator, a magnetostrictive unit

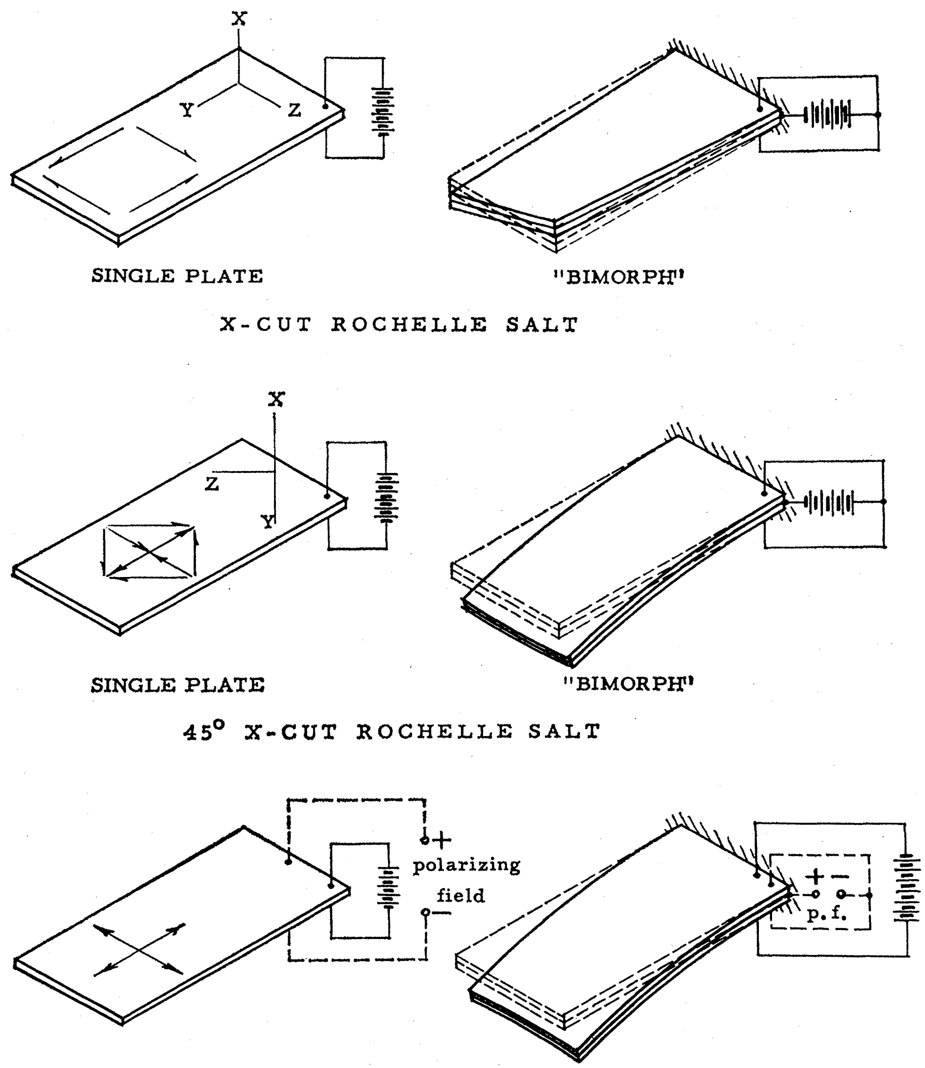


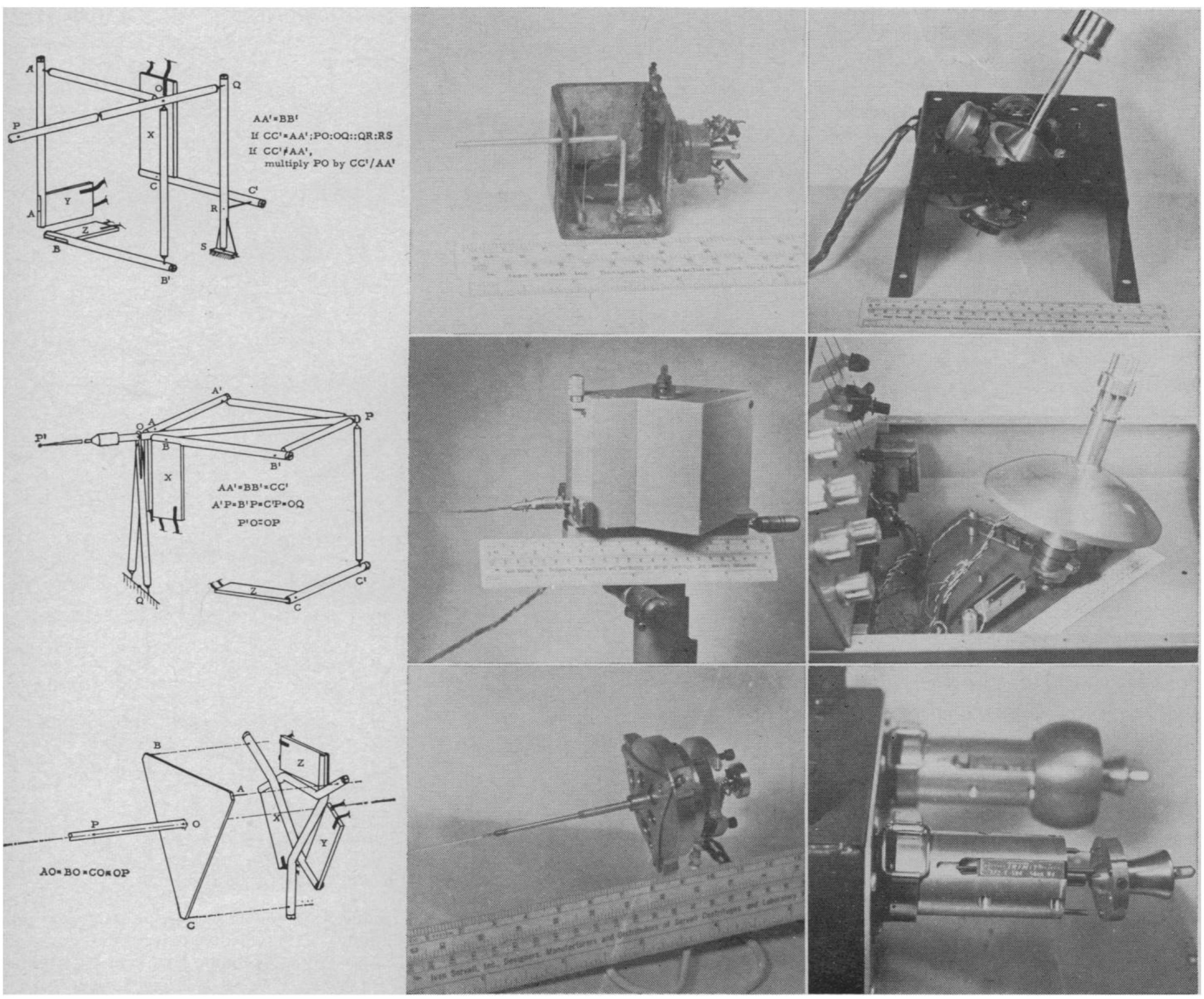
Fig. 1. Diagrams at left show the forces induced in single plates of Rochelle salt and barium titanate ceramics by electrical potentials applied to electrodes covering their major faces. In the *X*-cut Rochelle salt plate, shearing forces are induced parallel to the *Y* and *Z* crystal axes. In the 45-degree *X*-cut Rochelle salt plate the shearing forces are shown resolved into tensile and compressive components parallel to the edges of the plate. In the barium titanate plate no crystal axes are shown, since the microcrystalline components in the ceramic are randomly oriented. Instead, a permanent polarization has been induced by an electrical field applied to the face electrodes, as shown by the dashed-line circuits. Diagrams at right show the strains that result when two of the plates shown at left are cemented together and energized as indicated. The forces and strains indicated are reversed by a reversal in polarity of the applied voltage.

would have approximately ten times the linear dimensions of a piezoelectric unit. This and other considerations, such as the fact that a statically deflected piezoelectric transducer dissipates no power while a magnetostrictive transducer draws power as long as the deflection is maintained, have led to investigation of the potentialities of piezoelectric transducers for use in micromanipulators (9). The outcome of this investigation has been the design and construction of piezoelectric micromanipulators which satisfy the requirements outlined at the beginning of this section.

Piezoelectric Transducers

If a force is applied to a solid crystalline dielectric, the crystal lattice is distorted. If the charge distribution within the crystal lattice is asymmetrical, the lattice distortion results in a net relative displacement between the positive and the negative charges within the lattice. As a result of the internal charge displacement, equal and opposite external charges appear on opposite faces of the crystal (*10*). This is the direct piezoelectric effect first definitively studied by Pierre and Jaques Curie in 1880 (*11*). The Curies did not anticipate the converse piezoelectric effect but quickly established its existence after it had been predicted, on thermodynamic grounds, by Lippmann (*12*) in 1881. The converse piezoelectric effect is literally the converse of the situation described. If an electric field is established across a solid crystalline dielectric having an asymmetrical charge distribution in its lattice, a relative displacement of these charges is induced and a mechanical distortion or strain of the crystal results.

Since the direct and converse piezoelectric effects were discovered, many



Figs. 2 (top row), 3 (middle row), and 4 (bottom row). In each case the diagram at left shows the transducer linkage pattern of the operating head shown in the adjoining photograph. The photographs at right show the manual control transmitters used with each operating head. Fig. 2. The pilot model piezoelectric micromanipulator constructed in 1955 to test the feasibility of such a system. Fig. 3. The large piezoelectric micromanipulator. The cover of the control center has been removed to show the linkage between the manual control handle and the voltage-dividing resistors controlling movement in the horizontal plane. Fig. 4. One of the small piezoelectric micromanipulators designed for use as satellites on the large model. The hand grip of the nearer manual control transmitter has been removed to show its construction.

types of electromechanical transducers have been devised in which use is made of these phenomena. The extensive use of piezoelectric transducers in the field of acoustics has greatly simplified the problems encountered in the use of piezoelectric transducers in micromanipulators.

In the general class of piezoelectric materials there are some, typified by Rochelle salt (sodium potassium tartrate), with unusually large piezoelectric and dielectric coefficients. In investigating the piezoelectric properties of Rochelle salt plates cut with their major faces perpendicular to the *X* axis of the crystal, Valasek (*13*) observed hysteresis and saturation effects in both the piezoelectric and the dielectric coefficients in the temperature range −18° to 24°C. He drew an analogy between the characteristic anomalies of Rochelle salt and those of ferromagnetic materials. On the basis of this analogy piezoelectrics showing these characteristics have been called "ferroelectric" materials and the transition temperatures, Curie points (*14*).

Because the upper Curie point of Rochelle salt occurs near room temperature, the sensitivity of Rochelle salt transducers in the temperature range in which they would be most often used in a micromanipulator is exceedingly temperature-dependent. Acoustic transducers are also most frequently used at room temperature. As a result, the problems of temperature dependence, as well as those posed by hysteresis and saturation effects, have to a large extent been solved by persons concerned with the acoustical application of Rochelle salt transducers. Sawyer and Tower (*15*) observed that clamping a Rochelle salt *X*-cut plate virtually eliminated hysteresis and saturation effects. Sawyer (*16*) then described a type of Rochelle salt transducer in which two *X*-cut plates were fastened together so that each served as a partial clamp for the other. This type of transducer, in addition to having greatly reduced temperature dependence and greatly reduced hysteresis and saturation effects, provides amplification of the amplitude of displacement over that of single crystal transducer. The motion of Rochelle salt bimorphs (*17*) may be either a twisting about the long axis of the assembly (twister bimorph) or a bending of the assembly (bender bimorph), depending on the cut of the plates (Fig. 1).

Up until the last 10 years Rochelle salt bimorph transducers completely dominated the field of acoustical applications for piezoelectric transducers. Recently, ferroelectric ceramics, usually barium titanate ceramics, have been widely used in virtually all fields of application for piezoelectric transducers, with the exception of frequency-determining devices, which are still principally of quartz. These ceramics consist of barium titanate with a binding agent, plus varying proportions of additives to alter their electrical characteristics. Additives such as strontium titanate (*18*) modify the temperature dependence of the ceramic by shifting the Curie point; the addition of lead titanate (*10*) appears to increase the long-term stability of polarization, which in these materials must be applied artificially. These and other additives (*8*) can also modify the dielectric constant and the electrostrictive constant of the ceramic.

Ferroelectric ceramics, being polycrystalline structures having random orientation of the constituent crystals, do not show an intrinsic first-order piezoelectric effect. However, these materials are so strongly ferroelectric that the quadratic piezoelectric or electrostrictive effect is quite large. In the unpolarized ceramic, strain is proportional to the square of the applied field. When the finished ceramic element is subjected to a strong polarizing field (usually 1000 volts per millimeter or more) for a period of hours, a permanent polarization remains on removal of the applied voltage. Transducers so treated show a polarized electrostrictive effect that is for many purposes similar to the first-order piezoelectric effect of single ferroelectric crystals. These elements may be

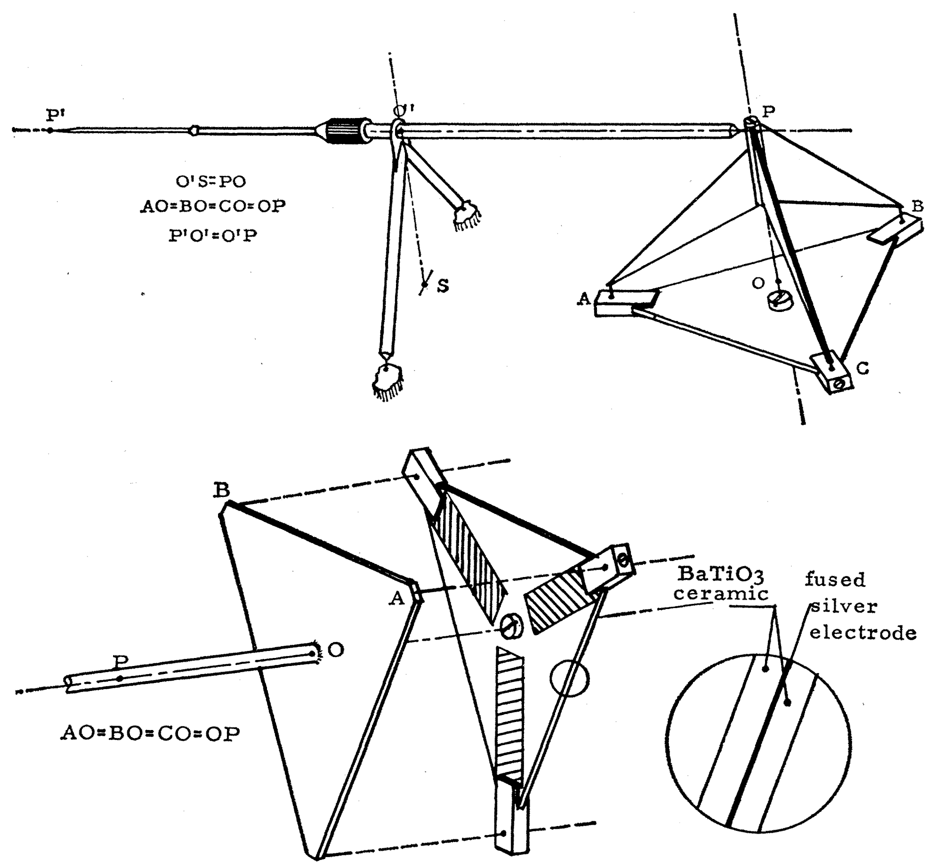


Fig. 5. (Top) Diagram showing how a single ceramic transducer could be used to provide three-dimensional movement. The shaded regions on the transducer show the outside electrode configuration. Similarly placed electrodes would be on the back of the transducer. The inside electrode covers the whole surface and would serve to join the two layers of the transducer. A transducer of this type would be polarized by a field applied between the inside electrode and the appropriate outside electrode. The linkage pattern of this head is essentially the same as that used in the satellite head shown in Fig. 4. Both systems suffer from the fact that the point along the tool axis at which the range of movement is equal in all directions is too close to the head for general use. (Bottom) A simple arrangement for correcting this deficiency.

used to make bender bimorphs but, since they cannot be made to operate in "face-shear" modes, are not usable as twister bimorphs.

The mechanical properties of these ceramics are superior to those of any piezoelectric other than quartz, and the magnitude of their quasi-piezoelectric coefficients can be made greater than those of Rochelle salt. These factors, coupled with the versatility of form possible with a ceramic material, have lead to the displacement by ferroelectric ceramics of other piezoelectrics in conventional applications and have stimulated the development of a myriad of new applications for piezoelectric materials. Unfortunately, most of these uses of piezoelectric transducers have involved conversion of transient mechanical signals into electrical signals, or the converse. As yet there has been little demand for piezoelectric transducers in steady-state or direct-current applications. The use of piezoelectric transducers in micromanipulators requires reliable performance in producing slow movements and in maintaining static deflections. Tests (*9*) of commercially available Rochelle salt transducers and barium titanate ceramic transducers showed that the Rochelle salt transducers were adequate in their response to direct-current or slowly varying signals, while the barium titanate transducers tended to drift and shift their rest position. These effects were presumably due to alteration of the "permanent" polarization of the ceramic transducers by the direct-current signals employed. Consequently, Rochelle salt transducers were used in all the piezoelectric micromanipulators described here. It is to be hoped that ceramic transducers with sufficient stability under direct-current signals will eventually become available.

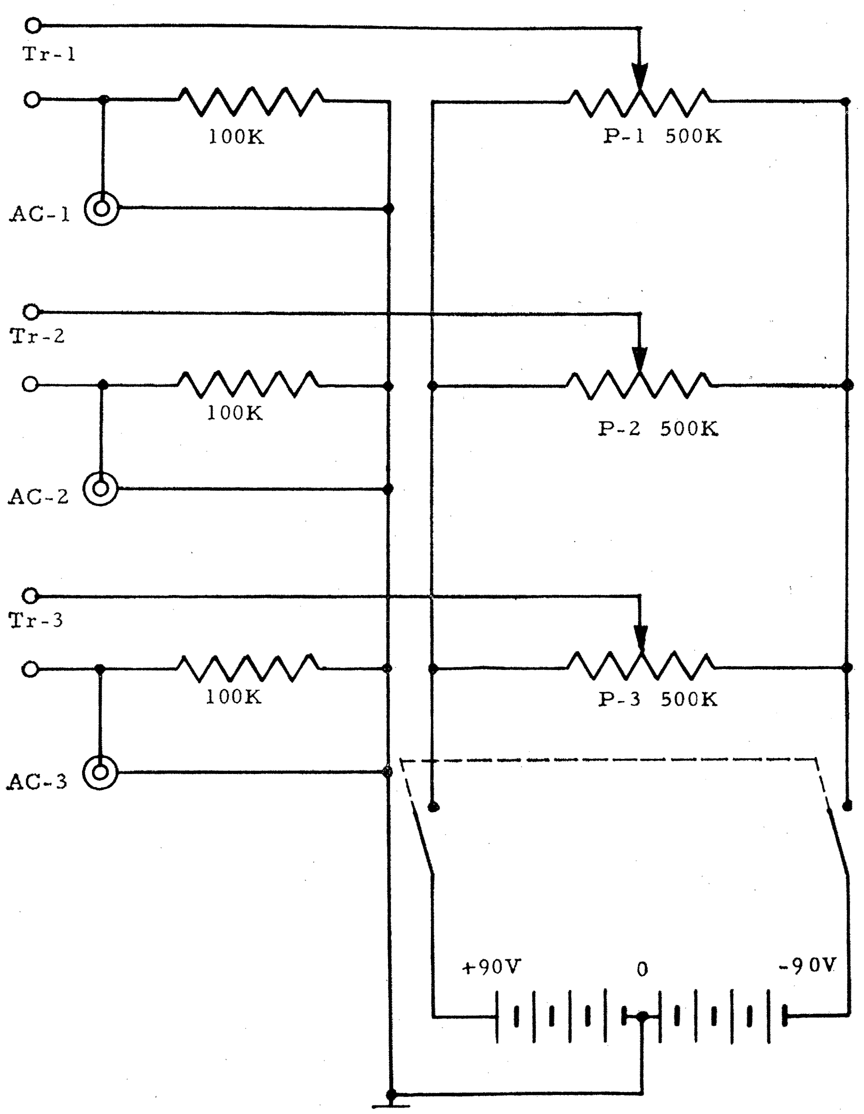


Fig. 6. The control circuit used with the pilot model and satellite operating heads. *P-1*, *P-2*, *P-3*, Voltage-dividing resistors in the manual control transmitter; *Tr-1*, *Tr-2*, *Tr-3*, leads to the operating head transducers; *AC-1*, *AC-2*, *AC-3*, input jacks for alternating-current signals to the transducers.

Design of Piezoelectric Micromanipulators

Once the transducer has been selected, the primary problem in the design of a piezoelectric operating head is that of linking the one-dimensional output of each of three transducers to a common shaft carrying the microtool. This linkage system should satisfy several requirements, some of which are mutually contradictory. To reduce susceptibility to externally imposed vibration and to insure transmission of high-velocity impulses from transducer to microtool, the linkage elements must be as rigid as possible. To achieve high acceleration with the limited force available from a given transducer, the moving mass must be kept to a minimum and friction in the linkage must be virtually nonexistent. As in any micromanipulator, lost motion in the linkage is intolerable.

Materials that are both rigid and weightless are hard to come by, so, as a compromise, lightweight aluminum alloy tubing was used for the principal elements of the linkage systems. Titanium alloys, when they become more widely available, may be a better choice. Friction was minimized and lost motion was avoided by the use of spring hinges fabricated of hardened steel wire (music wire).

The geometry of the transducer linkage should be simple and well defined, and it should permit the use of a mechanically simple control system. Three transducer linkage patterns used in actual operating heads are shown in Figs. 2–4, together with the head in which each was employed. In these heads twister bimorphs are employed, but the same linkage patterns would serve if bender bimorphs were substituted for each twister and its attached torque arm. Development of ferroelectric ceramics that could maintain constant characteristics under prolonged direct-current excitation would allow simplification of the linkage system. One possible configuration involving use of a single ceramic transducer is shown in Fig. 5.

The control system for use with these operating heads must, to satisfy the requirements set forth, be able to supply the transient signals required for automatic high-speed movement as well as provide a convenient means for converting an operator's hand motions into the electrical signals that will cause the operating head to move the microtool in a miniature duplication of these motions.

The manual control transmitter must resolve displacement of the control handle into components in each of the directions that correspond to directions of movement of the operating head transducers, and must transmit electrical signals proportional to each component of displacement to the appropriate head transducer. In a piezoelectric transducer, strain is proportional to the charge applied to the electrodes. Hence, the deflection produced by a given electrical signal is proportional to the product of the applied voltage and the capacitance of the transducer.

The capacitance of a piezoelectric transducer does change with strain, but in the units employed in these operating heads, deflection is sufficiently linear with voltage to allow control by voltage signals proportional to the displacement of the control handle. The proportional conversion of displacement into voltage is most easily accomplished with variable voltage-dividing resistors; accordingly, in the manual control transmitters [Figs. 2 (right), 3 (right), and 4 (right)], for each of the operating heads shown, use is made of variable voltage-dividing resistors for this purpose.

In the smaller operating heads, Rochelle salt transducers from phonograph pickups are used (*19*), and these can be controlled by simple, battery-powered circuits, as shown in Fig. 6. In the large piezoelectric operating head, Rochelle salt transducers from record cutters are used (*20*). These transducers have a capacitance of about 5000 to 7000 micromicrofarads and will tolerate an excitation signal of $\pm$ 150 volts. If the basic control circuit were to be used directly with these transducers, the voltage-dividing resistors would be required to dissipate excessive amounts of power, so in this case a cathode-follower amplifier is inserted between each voltage-dividing resistor in the manual control transmitter and the head transducer it controls. This arrangement makes it possible to use small voltage-dividing resistors of high resistance and low power dissipation in the control transmitter while driving the transducers in the operating head from a low impedance source, thereby improving the speed of their response to transient signals.

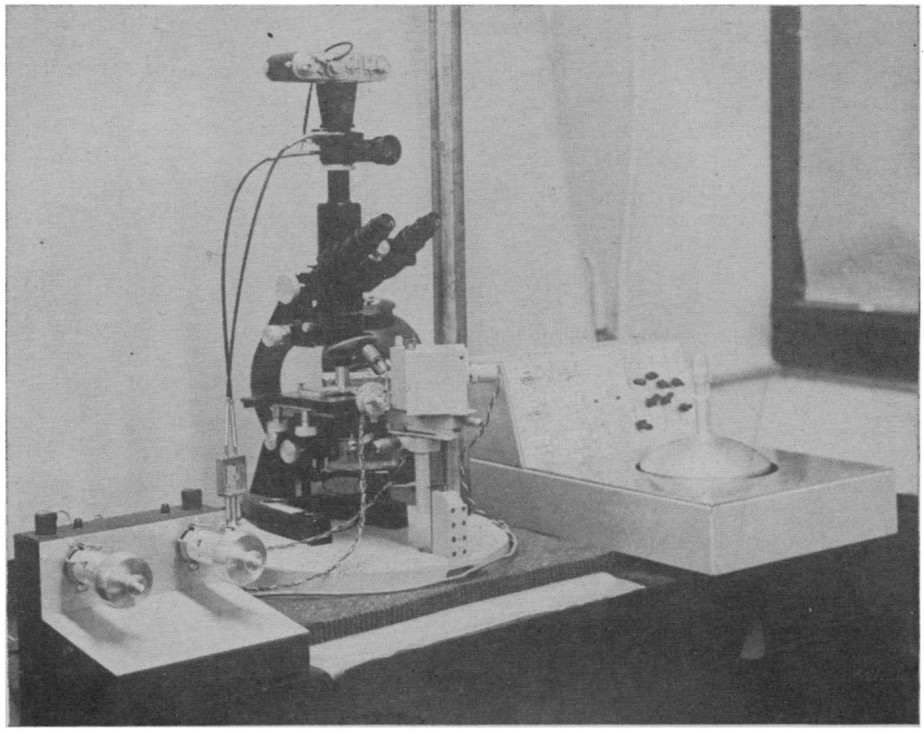


Fig. 7. A complete piezoelectric micromanipulator system. Controls for the satellite heads are at left; the control center for the large operating head is at right.

High-speed movements are accomplished by supplying one or more of the operating-head transducers with an appropriate voltage wave form. A single pulse produces a single thrust, while a continuous alternating current wave form produces tool vibration at the frequency of the excitation signal. Signals for producing high-speed movements may be derived from an external source or, as in the case of the control center (Fig. 7) for the large operating head, from a built-in oscillator. In this unit the direction of high-speed tool movement is controlled by switches that allow preselection of the head transducers that are to receive the signal. A phase inverter following the oscillator makes the signal available for selection in either direct or inverted form. An oscillator function-selector switch presets the oscillator for production of single pulses or continuous saw-tooth waves, whose frequency and amplitude may also be preset by controls on the front panel. A third position on the function-selector switch selects signals from an external source through a built-in preamplifier. Signals from external sources may also be presented directly to the grid of each cathode-follower amplifier. Activation of the oscillator or admission of signals to the preamplifier is controlled by a momentary-contact switch on the handle of the manual control transmitter.

The reduction ratio between hand and tool movement in the horizontal plane is controlled by a four-position switch on the front panel of the control center. The first position is fixed at the minimum reduction ratio; the other three can be adjusted to complement each of three different microscope magnifications. Manual control of vertical movement is, as in the de Fonbrune micromanipulator, accomplished by rotating a knob at the top of the manual control handle. A separate knob on the front panel controls the reduction ratio for vertical movement. Reversing-switches for each of the control directions are mounted on the front panel in order that the apparent direction of movement of the microtool image may be made to follow the movement of the control handle regardless of the type of microscope employed.

The piezoelectric micromanipulators described here are designed for use at high microscope magnification and have a limited range of tool movement. In the case of the large operating head, the maximum tool movement is about 600 microns. Consequently, there must be some means of initially positioning the microtools with respect to the microscope field. In use, the large operating head is carried by a three-dimensional mechanical micropositioner. The positioning device allows preliminary positioning of the microtools and, in addition, permits rapid withdrawal and return of the microtools, by means of a cam-operated slide, to facilitate changing the subject of the operation. When withdrawn, the head may also be rotated away from the microscope for replacing broken tools. The satellite operating heads carried by the large head have positioning screws that allow alignment of the satellite microtools with the principal tool. These positioning mechanisms may be seen in Fig. 8.

Performance

The piezoelectric operating heads shown in Figs. 2–4 will respond, with reasonably good correspondence between signal voltage and tool displacement, to signals ranging from direct-current signals up to low audio frequencies. At higher excitation frequencies, mechanical resonance in the transducers, and particularly in the linkage system, modifies the amplitude and the direction of movement of the microtool tip. However, even with the relatively compliant linkage systems used in these operating heads, a microtool may be vibrated with a usable amplitude at frequencies in excess of 30 kilocycles per second.

Under manual control, tool movement follows hand movement smoothly, without perceptible lag or overshoot. However, tests have shown that response to a large step change in applied voltage is in two parts. The first is a rapid displacement to about 95 percent of the final displacement, followed by a slower approach to the final position. This effect may be due to flow in the plastic coating used to waterproof these Rochelle salt transducers, or it may be a function of the electrode contact with the crystal surface (*21*). In any event, the slow component of the movement is rapid enough to be ordinarily undetectable under manual operation, and it has negligible effect under pulsed or alternating current operation.

The deflection sensitivity of the large head is about 2 microns per volt. The range of movement for this head is, as stated previously, about 600 microns in any direction. The pilot model has a range of about 300 microns in any direction, while the small heads used as satellites on the large operating head have a range of about 150 microns in the direction of the microtool axis and about 500 microns normal to this axis.

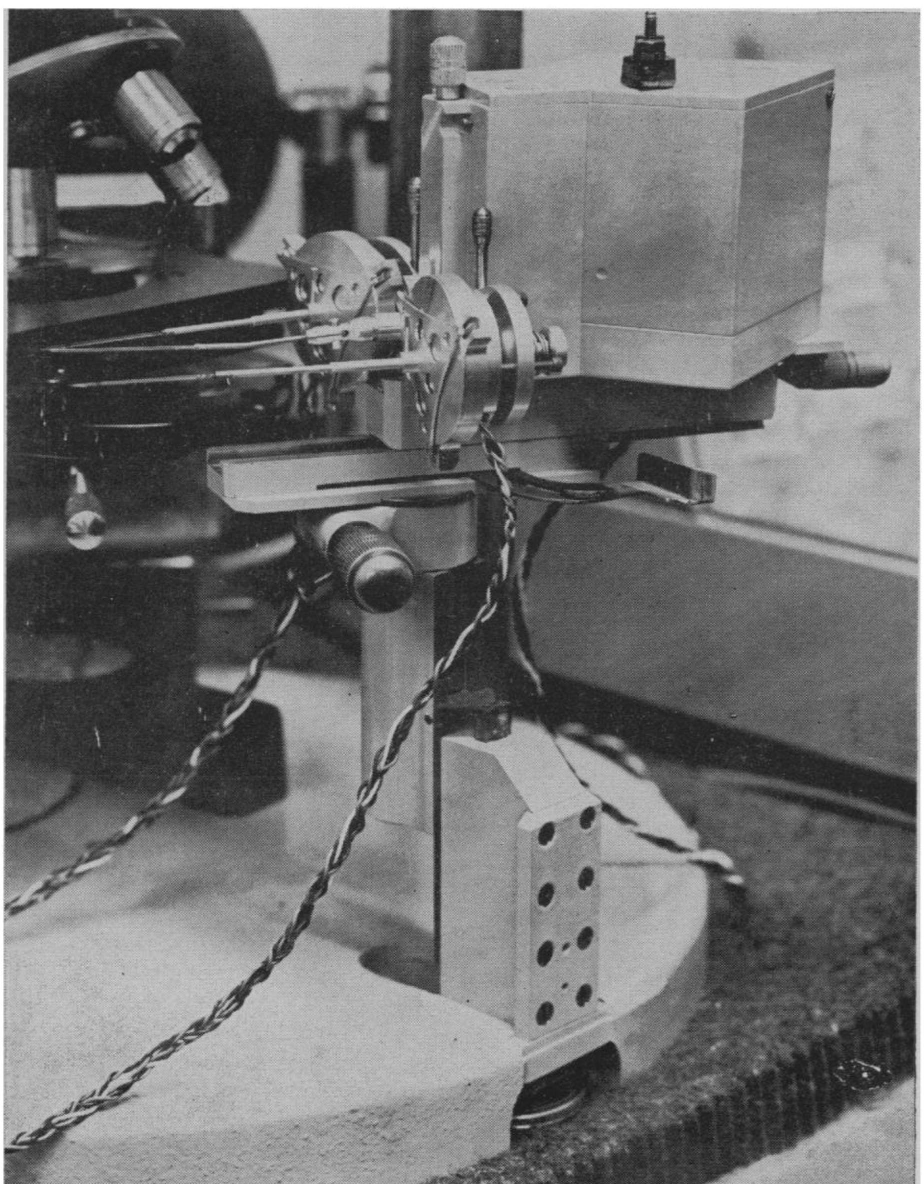


Fig. 8. The large piezoelectric operating head with its two satellite heads in place. The heads are mounted on the mechanical micropositioner referred to in the text.

Applications

Piezoelectric micromanipulators are well suited for use in all types of microdissection experiments under high magnification, particularly where penetration of membranes is a critical problem. I have used the instruments described (*9, 22*) to investigate the effects of mechanical injury of the cell nucleus.

In addition to their use in biological investigations, piezoelectric micromanipulators may find important new uses in the development of semiconductor devices and microcircuits. For example, semiconductor junctions could be formed by microetching and electroplating with microelectrodes. Complex circuit paths could be formed by etching through a conducting layer deposited on an insulating substrate. The virtue of the piezoelectric micromanipulator in this application lies in the fact that it is controlled by electrical signals. These could be recorded on magnetic tape while a given operation is being performed manually, then played back through the operating head to repeat the operation. With these techniques, complex circuits of unprecedentedly small size could be fabricated automatically. If such a scheme should prove feasible, the microcircuits produced could, in turn, have important applications in biomedical research.

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Molecular Designing of Materials

Science, guided by molecular understanding, takes up the challenge to create materials for the future.

Arthur R. von Hippel

Exploration of the resources of our planet, only a generation ago still left to the individual prospector, geologist, or mining engineer, is now a joint concern of the scientific world community, as the recent International Geophysical Year testifies. Our present knowledge of mineral resources has been summarized with penetrating understanding by Meyerhoff (*1*). How to sustain an explosively growing world population is the theme of pioneering studies like those of Harrison Brown (*2*). Catastrophe will be the assured outcome of this situation if political and economic insight cannot win the race against prejudice and ignorance. It is the unhappy fate of the scientist today that he must play the role of Cassandra in the body politic, sending his fellow men to bed with nightmares in the hope of being heard in time.

Fortunately, an article on the molecular designing of materials need not be gloomy; on the contrary, I want to report on developments bright with promise, starting with the apparently naive question: What shall we most reasonably do with our natural resources? In earlier times the answer was simple: Here are the materials found in nature and transformed by industry; there are their macroscopic properties, defined and tabulated. Add the practical experience of the engineer and the economic incentive of maximum profit. Into this mold our demands had to fit, rudely deprived of soaring imagination.

Suddenly all this is changing. "Molecular science"—in decades of quiet studies on electrons, atoms, molecules, and their concerted action in gases, liquids, and solids—has made a more powerful approach possible: "molecular engineering," the building of materials and devices to order. We begin to design materials with prescribed properties, to understand the molecular causes of their failings, to build into them safeguards against such failure, and to arrive at true yardsticks of ultimate performance. No longer shackled to presently available materials and characteristics, we are free to dream and find answers to unprecedented challenges. Simultaneously we begin to foresee, in ever-widening perspective, the consequences of our actions. It is about this revolutionary situation, which makes scientists and engineers true allies in a great adventure of the human mind, that I am going to speak (*3*), though fully aware that most facts here presented are well known to the specialist and that I need your indulgence for trying to unfold a great panorama despite limited insight.

The Web of Electron Clouds

When an ultimate Power created protons and electrons, the basic building laws for this world were decided. The two particle types, equipped with equal but opposite elementary electric

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