Application Note 4

Picomotor Drivers: A Guide to Computer Control and Closed-Loop Applications

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Introduction

The Picomotor—a piezoelectric actuator that turns a screw—allows mounts, stages, and micrometer-replacement actuators to achieve <0.1-µm resolution with remote control or manual adjustment capability. Fig. 1 shows how the Picomotor works much like your own fingers. Two jaws grasp an 80-pitch screw, and a piezoelectric transducer (piezo) slides the jaws in opposite directions just as your thumb and forefinger would. Slow action of the Picomotor causes a screw rotation, while fast action, due to inertia, causes no rotation. An electronic driver generates the high-voltage pulses necessary to activate the piezo in the Picomotor. This driver alters the direction of screw rotation by changing the rise and fall times of the pulse. The screw does not turn during fast rise or fall times. Hence, a pulse with a fast rise time and a slow fall time generates a counterclockwise rotation, while one with a slow rise time and a fast fall time generates a clockwise rotation.

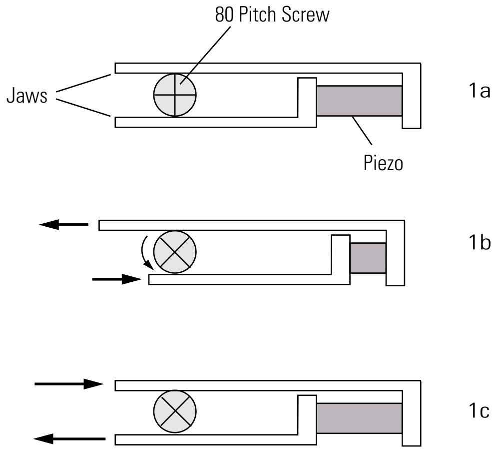

Fig. 1: Schematic of the action of the Picomotor. Two jaws grasp an 80-pitch screw (1a), and a piezoelectric transducer slides the jaws in opposite directions. Slow action of the Picomotor causes a screw rotation (1b), while fast action, due to inertia, causes no rotation (1c).

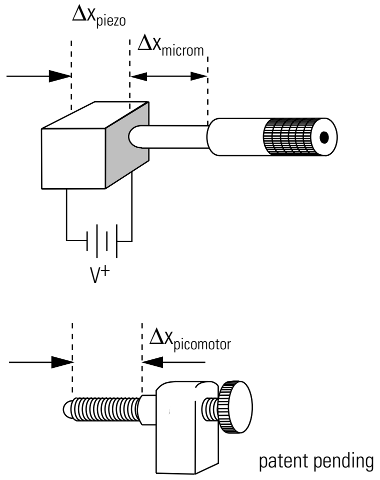

Fig. 2: Comparison of a conventional piezo-driven actuator and a Picomotor. The conventional actuator's extension is the sum of the extensions of the piezoelectric material and the micrometer. In the Picomotor, the piezo is used only to turn the screw and not to hold the adjusted position leading to greater stability and ease of use.

The Picomotor does not exhibit some of the problems commonly associated with piezo-driven actuators. Fig. 2 shows a conventional piezo-driven actuator and a Picomotor. The conventional actuator's extension is the sum of the extensions of the piezoelectric material and the micrometer. This arrangement is used to provide coarse (with the micrometer) and fine (with the piezo) motion control. Since the extensions of the two actuators are independent, it is necessary to adjust the coarse control to keep the fine control from saturating. Also, the voltage on the piezo must be kept constant to maintain a constant extension. However, constant voltage applied to a piezoelectric material leads to creep—a slow change in the piezo's displacement over time, which affects the actuator's position. In the Picomotor the piezo is used only to turn the screw and not to hold the adjusted position; therefore, the set position can be maintained even when the power is removed or the Picomotor is disconnected from its driver. Also, coarse and fine controls combine to produce the same result, a rotation of the screw, eliminating the possibility of running out of fine tuning range.

A problem that conventional piezo-driven actuators and Picomotors share is that of repeatability. The piezoelectric material in a conventional actuator has a multi-valued and nonlinear extension versus voltage. The practical consequence of this phenomenon, known as hysteresis, is that the actuator's displacement cannot be determined solely by the applied voltage. A Picomotor does not exhibit hysteresis, but small variations in screw rotation from step to step can lead to similar repeatability errors. These errors are accentuated if the force acting against the Picomotor's motion differs significantly from step to step. This condition is known as nonuniform loading and occurs when the Picomotor acts against a spring, or is used to lift and lower objects.

External Inputs

Only two control signals are necessary for a Picomotor's operation: a step command and a direction indicator. Rotation rate is determined by the frequency of the step commands. A block diagram of one axis of a Picomotor driver is shown in Fig. 3. The Logic box accepts the step and direction commands and generates signals that operate the power field-effect transistors (FETs). These power transistors and their associated circuitry generate the high-voltage pulses that turn the screws.

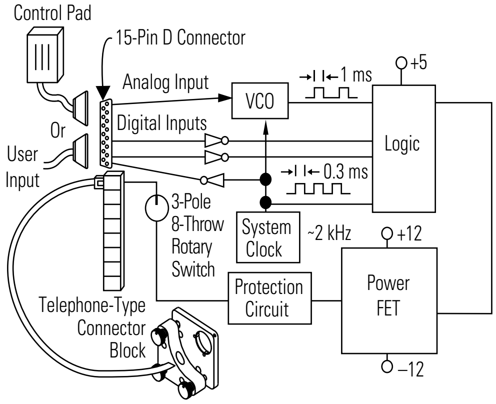

Fig. 3: Block diagram of one axis of a Picomotor driver. The Logic box accepts the step and direction commands from the D connector (see Fig. 4), and generates signals that operate the power FETs. These power transistors and their associated circuitry generate the high-voltage pulses that turn the screws.

The Picomotor Models 8801 and 8701 multi-axis and single-axis drivers accept both analog and digital signals through a 15-pin connector shown in Fig. 4. Analog or digital control will produce the same result and it is not necessary to use both kinds of input. In analog signal mode (for example, using the remote-control pad or applying a signal to pins 1, 6, or 2 to control Picomotors A, B, or C, respectively), a bipolar-analog input from -2.4 V to +2.4 V causes the voltage-controlled oscillator (VCO) block to generate a stream of 1-ms pulses synchronous with the system clock. The frequency of the pulses varies from 1 per second for analog inputs of +100 mV and -100 mV to 1,000 per second for analog inputs of +2.4 V and -2.4 V. The pulse rate varies as the magnitude of the input signal, while the 100-mV threshold prevents noise from actuating the piezo. The sign of the analog input determines the rotation direction with positive values causing counterclockwise rotation. One complete revolution of the screw requires at most 30,000 pulses, hence the maximum rotation rate is ≥2 RPM. Faster coarse adjustment can always be done by hand.

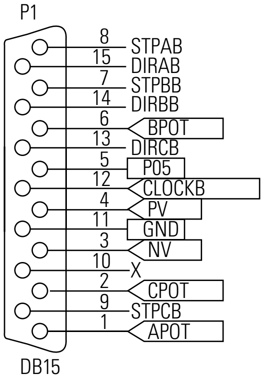

Fig. 4: The 15-pin D connector used in the Model 8801 and 8701 drivers to accept analog and digital inputs.

Digital control involves applying a series of step pulses to pins 8, 7, or 9 and setting a rotation-direction level at pins 15, 14, or 13. Picomotor drivers shipped after July 1, 1994 include a synchronization circuit (see Fig. 5 and the next section) that simplifies digital control. The Picomotor will step each time a falling edge is applied to its STP input, in a direction determined by the DIR input. A high level (+5 V) indicates a clockwise rotation. Maximum rotation rate is achieved for an input frequency of 1 kHz; higher frequency inputs do not result in an increased rotation rate.

Synchronization

A pulse of 1-ms duration is required by the driving electronics to digitally step the Picomotor. Synchronization of this digital control signal with the system clock is required to prevent wobble and random angular motion of a driven mount. Picomotor drivers shipped after July 1, 1994 include a built-in synchronization circuit to simplify digital control. A similar circuit that can be built to accomplish this synchronization on earlier drivers is shown in Fig. 5. The circuit is drawn to synchronize screw A, and similar circuits may be used to drive B and C. On a falling edge of the EXT STP control line, the D flip-flop U1A will clock in a high and U2A will clock in the EXT DIR input. On the next rising edge of CLK, the inverted system-clock output from the Picomotor driver, a high will be clocked into U1B, setting pin 8 low. This clears U1A and sends a step command to the Picomotor driver. On the same CLK edge, U2B will clock in the direction that was stored in U2A. On the next rising edge of CLK the low will be clocked into U1B, driving pin 8 high. This terminates the step and makes U1A ready for another STP input trigger. Thus a negative going pulse of exactly one clock cycle in width has been generated on the step-input line, STPAB. U2B holds the direction information until the next step. The CLR line sets the initial state on power-up. It should not be driven low until 1 ms after the last command.

Applications

The Picomotor's ability to fine-tune position with a wide dynamic range makes it ideal for position control applications. Fig. 6 shows the Picomotor controller used in a closed-loop system that maintains the alignment of an interferometer by adjusting the tilt of one of the mirrors. A quadrant photodetector[1] has been added to the Michelson interferometer used to demonstrate the mechanical stability of New Focus mirror mounts. The basic Michelson interferometer consists of a He-Ne laser, Beam Splitter 1, Mirror 3, and Mirror 4. The interference-fringe pattern from the reflections off Mirrors 3 and 4 is shown on a Screen. Lenses 1 and 2 expand the beam to make a large interference pattern.

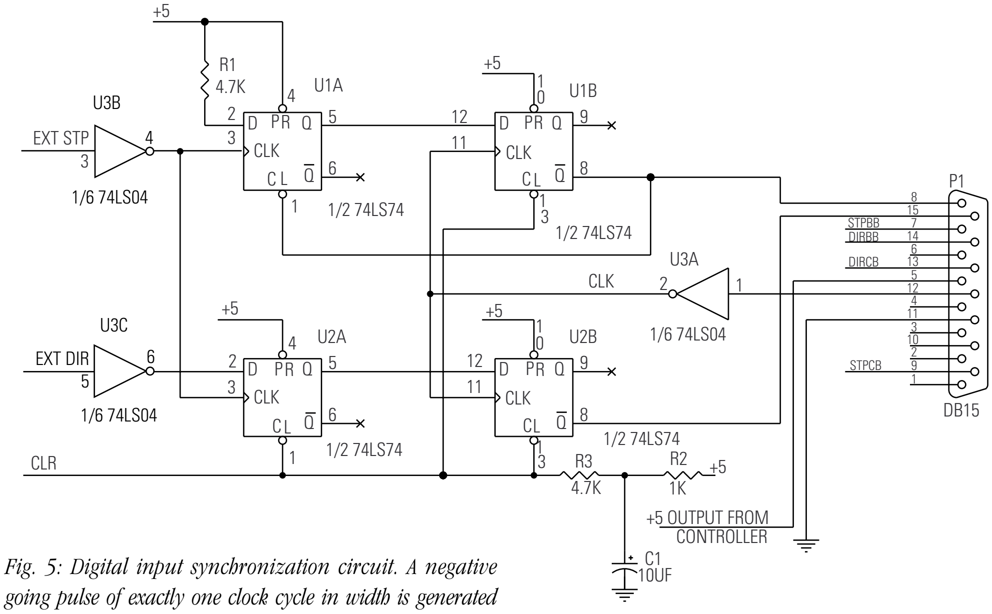

Fig. 5: Digital input synchronization circuit. A negative going pulse of exactly one clock cycle in width is generated on the Picomotor step-input line.

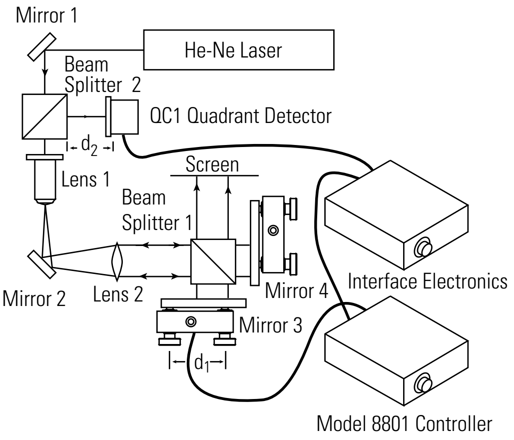

Fig. 6: Schematic of a sample closed-loop system that maintains the alignment of an interferometer by adjusting the tilt of one of its mirrors.

To sense the relative positions of Mirrors 3 and 4, Beam Splitter 2 was inserted into the beam path. This beam splitter directs some of the reflections from Mirrors 3 and 4 onto the quadrant photodetector, QC1, where they are imaged as small points. The quadrant detector is centered on the retroreflection from Mirror 4. QC1 is oriented as shown in Fig. 7. It generates four photocurrents that are related to the portion of the optical beams striking each quadrant. The four photocurrents are sent to the interface electronics where they are individually amplified[2], as shown in Fig. 8. The position sensitivity of the quadrant-detector circuit depends on the detector responsivity, the beam size, and the electronic gain. It is usually adjusted by varying the transimpedance (100 k**Ω** in this case) of the photocurrent amplifiers. In the system shown in Fig. 6, the electronic gain is chosen such that the photodiode signals correspond to 1 V/mm of beam displacement in each direction, as measured by simply translating the optical beam a known amount. The amplified photodiode signals are subtracted to generate a top-minus-bottom signal (UP) and a right-minus-left signal (RIGHT). For an optical beam nearly centered on the detector, the difference signals are directly proportional to beam displacement from the detector's center.

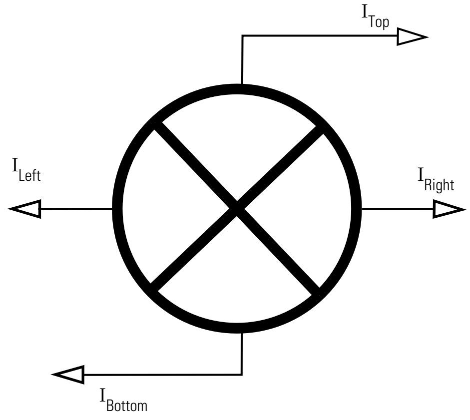

Fig. 7: Alignment of the quadrant photodiode used to measure the position of the optical beams in Fig. 6.

The UP and RIGHT error signals are fed to the analog inputs of the Model 8801 multi-axis driver and used to control the position of Mirror 3. Because the retroreflection from Mirror 4 is centered on the photodetector, it does not contribute to the error signals. Any misalignment of Mirror 3 with respect to the detector's center generates an error signal and hence a correction by the Picomotor driver. The relative position of Mirrors 3 and 4 remains constant; therefore, the feedback loop maintains a constant fringe pattern.

The pointing error in this alignment system is estimated by dividing the 100-mV threshold of the Picomotor driver by the rest of the feedback-system gain, as shown in the system block-diagram of Fig. 9. The system gain is 30 (the differential gain of the error signals) times 1 V/mm (from the quadrant detector) times 80 (the geometric expansion of the lens system $2\,M\,d_1/l$, where M=20 is the magnification of the telescope, l=1.625 in is the distance from the Picomotor to the rotation axis of the mirror mount, and d_1=3.25 in is the distance between the quadrant detector and the first lens in the telescope). Therefore the pointing error is 42 nm in each direction. A derivation of the geometric expansion of the lens system[3] is shown in Fig. 10. A small Picomotor motion Δx_1 results in a mirror deflection $\theta \approx \Delta x_1/l$. The return beam is deflected by 2θ, which is increased f_2/f_1 times by the telescope. Therefore, the beam translates by

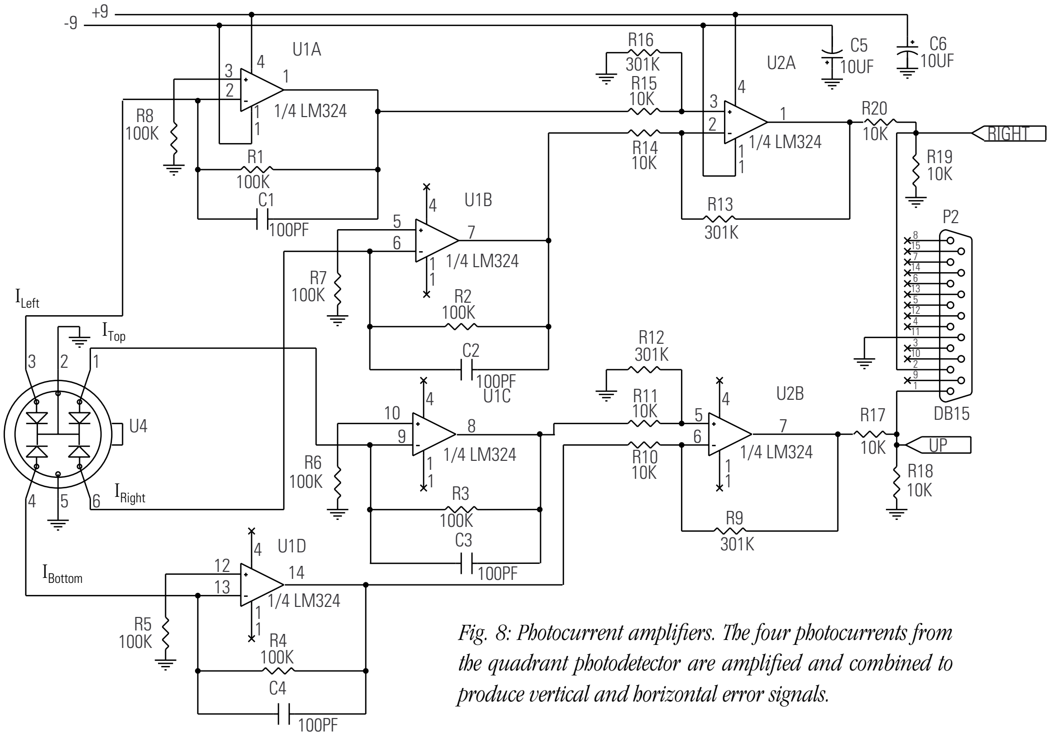

Fig. 8: Photocurrent amplifiers. The four photocurrents from the quadrant photodetector are amplified and combined to produce vertical and horizontal error signals.

roughly $\Delta x_2 \approx 2(f_2/f_1)(d_1/l)\Delta x_1$. An alternative to this theoretical calculation is to measure the loop gain directly. In the system shown in Fig. 6, simply translating the Picomotor a known amount (100 pulses for example) and measuring the resultant error voltage (UP or RIGHT) will do the trick.

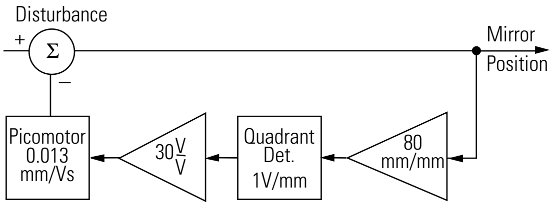

Fig. 9: Feedback system block-diagram. The pointing error in the alignment system is estimated by dividing the 100-mV threshold of the Picomotor driver by the feedback system's open-loop gain.

The error analysis shows that a high system gain reduces the resultant error, but this gain cannot be made arbitrarily high without compromising loop stability.[4] Specifically, the Picomotor driver has a pole at 400 Hz in its response to an analog input, and the detector electronics has a pole at 16 kHz. The feedback system also has a pole at the origin that occurs because one is sensing position and controlling velocity (much the same as one senses phase and controls frequency in a phase-locked loop[5]). The "voltage-controlled velocity" of the Picomotor can be estimated as follows: a full-scale 2.4-V signal applied at the input causes an average screw translation of 30 nm at a rate of 1000 times per second, leading to a gain of 0.013 mm V^{-1} s^{-1}. The combination of three poles will become unstable if the loop gain is too high, although a simple small-signal analysis is complicated by the Picomotor driver's threshold. Also, at high loop gains amplified electronic noise will be large enough to exceed the Picomotor's threshold causing it to constantly chatter. This consideration led to the particular choice of loop gain given above.

A similar feedback system could be used to fix the absolute position of a laser beam in space. Fig. 11 shows a system similar to one built by Grafström *et al.*[6] It uses two quadrant photodetectors as the two reference points that define a line in space, and two Picomotor actuated mirrors (such as our 8809 corner mounts) to control beam position. The point P1 on mirror M2 is imaged onto the first quadrant photodetector QD1. The difference signals from this detector are used to control mirror M1 and keep the laser beam centered on P1. With the beam position fixed, mirror M2 can be used to point the laser beam. Again a quadrant photodetector, QD2, is used to generate error signals which drive mirror M2 and keep the laser beam centered on P2. Choosing P1 directly on mirror M2 keeps the two feedback loops independent and the feedback system simple. Electronically actuated mirrors have also been employed by Sampas and Anderson[7] to automatically align and mode-match a laser beam to an optical resonator.

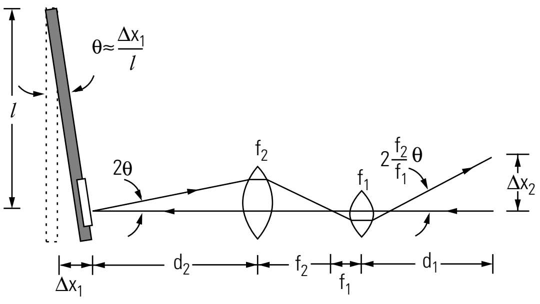

Fig. 10: A derivation of the geometric expansion of the lens system. A small Picomotor motion Δx_1 *results in a minor deflection* $\theta = \Delta x_1/l$. *The return beam is deflected by* 2θ *which is increased* f_2/f_1 *times by the telescope. Therefore the beam translates roughly* $\Delta x_2 \approx 2(f_2/f_1)(d_1/l)\Delta x_1$.

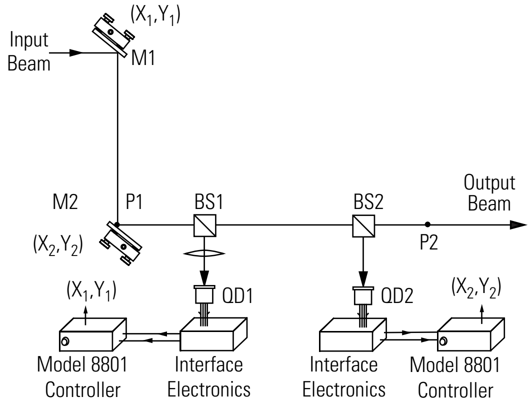

Fig. 11: A sample feedback system that fixes the absolute position of a laser beam in space. Points P1 and P2 define the two points in space through which the laser beam will propagate.

Summary

The Picomotor provides a simple and robust way to electronically actuate mechanical mounts. By using a piezo to turn a screw, creep is eliminated and an unlimited fine-tuning range is realized. The Picomotor single- or multi-axis drivers allow either manual operation of the Picomotor through a remote-control pad or automated control through a simple analog or digital electronic interface. Picomotors can be applied to any number of automated pointing or alignment applications.

References

[1] Most manufacturers of photodetectors also manufacture quadrant photodiodes; call us for more details.

[2] See P. Horowitz and W. Hill, *The Art of Electronics* (Cambridge, Cambridge University Press, 1990), for this and similar circuits.

[3] M. Klein, *Optics* (New York, James Wiley and Sons, 1970), is a good source for geometrical optics and the angular magnification properties of a Gallilean telescope.

[4] See G. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems* (Menlo Park, Addison-Wesley Publishing, 1988), for more on control theory.

[5] J. Smith, *Modern Communications Systems* (New York, McGraw-Hill, 1986), Chapter 9 has a good discussion of phase-locked loops.

[6] S. Grafström, U. Harbarth, J. Kowalski, R. Neumann, and S. Noehte, "Fast laser beam position control with submicroradian precision," *Opt. Commun.* **65**, p. 121.

[7] N. M. Sampas and D. Z. Anderson, "Stabilization of laser beam alignment to an optical resonator by heterodyne detection of off-axis modes," *Appl. Opt.* **29**, p. 394.

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