Application Note 6

Applications of the Picomotor™ in the Semiconductor Industry

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Introduction

Motion-control systems enable you to automate tasks as well as to make high-resolution adjustments in remote or hostile environments. For instance, traditional motion-control systems (i.e., stepper motors and servo motors) are widely used for accurately and repeatedly moving objects along a specified curve. Specifically, they have been used to automate processes, such as transferring parts along an assembly line or moving a workpiece in relation to a cutter. In the optics world, however, applications typically have more to do with optimizing and holding a position—“set-and-hold” applications—rather than repeating a process.

To address the specific needs of the optics industry, New Focus designed the patented Picomotor. It offers 30-nm resolution over as much as a 2" travel range, all in a compact package (only 0.63" wide). Moreover, it has exceptional long-term stability, and the ability to hold its position with no power applied. These last two features make the Picomotor unique among motion-control devices and ideal for typical set-and-hold applications. Such applications include precision control of sample holders inside cold and/or vacuum chambers, hands-off adjustment of mirror mounts that cannot be reached (like those in the center of a large setup), or adjustments of optical mounts that are sensitive to forces applied while twisting a knob (like when optimizing the alignment of a laser cavity or while adjusting the pointing of a beam over a long distance). The Picomotor can also be manufactured to be vacuum (10^{-6} Torr) compatible as well as non-magnetic, so it can be used in electron-beam applications.

In the semiconductor industry, two examples of how the Picomotor has been applied include a wafer-height adjustment system and an actively controlled laser-beam stabilization system. In the first example, the Picomotor is used for tip, tilt, and Z-adjustment of the semiconductor wafer and microscope platforms. By using the Picomotor, the height and orientation of the platforms can be remotely adjusted and then held constant for a scan, due to the Picomotor’s unique power-off locking feature. In the second example, the Picomotor is used to actively maintain a laser’s beam position, reducing the laser’s pointing instability (drift)—the main limitation behind wafer, mask, and reticle inspection systems. After a brief discussion of the Picomotor itself, and a comparison of it with other types of motion-control systems, this application note will discuss the details of these applications.

How the Picomotor Works

The Picomotor—a piezoelectric actuator that turns a screw—allows mounts, stages, and micrometer-replacement actuators to achieve 30-nm resolution with remote control or manual adjustment capability. Figure 1 shows how the Picomotor turns a screw much like you would with 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.

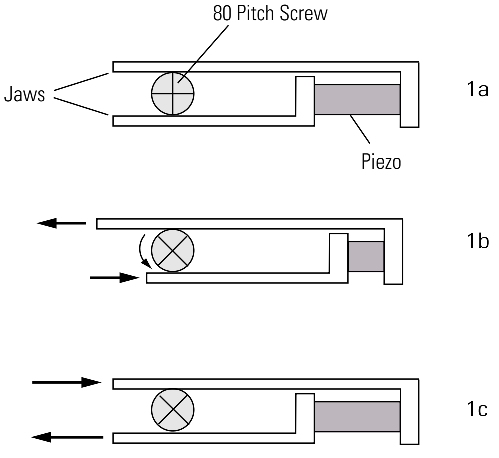


Figure 1: Schematic of the action of the Picomotor. Two jaws grasp an 80-pitch screw (1a), and a piezoelectric transducer slides the jaws in opposite directions. Slow action of the Picomotor causes a screw rotation (1b), while fast action, due to inertia, causes no rotation (1c).

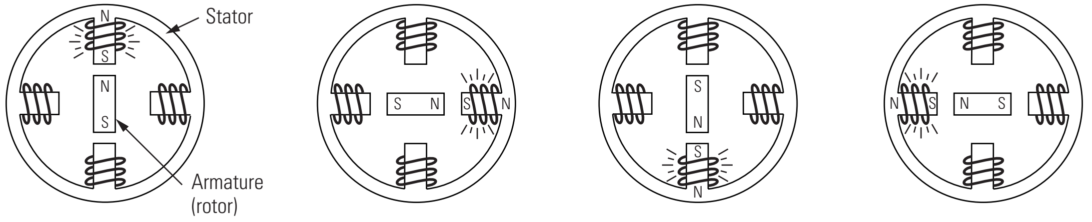
The device’s operation relies on the difference between static and dynamic friction. A helpful example of this principle in action is the “tablecloth” trick, in which a quick pull of the cloth leaves the dishes on the table (low dynamic friction), while a slow pull of the tablecloth pulls the dishes off the table (high static friction). Similarly, slow action of the Picomotor causes a screw rotation, while fast action, due to rotational inertia, causes no rotation. An electronic driver, equipped with full GPIB/RS232, analog, and TTL input capabilities, 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. Because the piezo is used only to turn the screw and not to hold the position, these devices can hold position indefinitely in the power-off state.

Comparison of the Picomotor with Other Types of Motors

Motion control in the past has been dominated by servo and stepper motors, or hybrid motors that combine these traditional rotary motors with ferroelectric tips such as those made from piezoelectric or electrostrictive materials. In general, these bulky motors require an applied voltage or a brake to maintain a specified position. Since accurate motion in some cases is more important than holding the specified position accurately, these actuators have provided satisfactory solutions. In the optics world, however, where set-and-hold applications are dominant, these motors have been unsatisfactory. Because of the Picomotor's compact size, its ability to hold the adjusted position in the power-off state, and its exceptional long-term stability, it is ideal for these applications as well as those where space is limited.

For example, let's compare the Picomotor to the common DC servo motor. The bulky DC motor consists of an armature—coils of wire around a metal core—inside a magnetic field. When current is applied to the windings, the armature interacts with the magnetic field causing the armature to turn. A motorized micrometer therefore consists of a DC motor coupled to a micrometer. Although this combination can achieve high resolution and smooth motion at high speeds, it is not an ideal solution for set-and-hold applications because it either requires constant power or an external brake to maintain position. In addition to being much larger than the Picomotor, it also generates a significant amount of unwanted heat.

In comparison, the commonly found, but bulky, stepper motor has been used for set-and-hold applications because it does not necessarily require a "brake" or "holding voltage" for a given period of time. Stepper motors use the principle of magnetic attraction and repulsion to move a screw. (See Figure 2.) By alternately applying current to the individual windings in the motor's stator, you create a torque that turns a permanent magnet and/or iron rotor. When the windings of the stepper motor are energized, a holding torque is generated; the motor moves only when that current is switched from winding to winding. Because digital pulses must be used to provide the rotation, stepper motors rotate in discrete steps. By interpolating between steps (called half-stepping and micro-stepping), resolution up to 10 nm and absolute accuracy to a micron has been achieved. Unlike servo motors, stepper motors have an inherent holding or detent torque that can be used to maintain position in the power-off state for a period of time. Picomotors don't have the high degree of repeatability of stepper motors, but stepper motors are bulky compared to the 0.63" x 1.25" Picomotor, and



Step 1 Step 2 Step 3 Step 4

Figure 2: Rotation in a stepper is achieved by alternately applying current to the individual windings in the motor.

they provide no manual adjustment capability. The large size of the stepper motor makes them difficult to incorporate into mirror mounts, and so they are typically used for optical delay lines.

Finally, let's compare the Picomotor to the simple piezoelectric device. In a simple piezo-based device, the piezoelectric material expands and contracts in response to an applied electrical voltage. The range of travel is limited, but it is very fast and provides extremely fine control. (Often it is integrated with a screw, as shown in Figure 3.) Because the expansion of the material is a direct measure of the voltage applied, constant power must be applied to hold the adjusted position. Although the Picomotor also uses a piezo, it doesn't rely on the piezo's expansion and contraction to act as the positioning element.

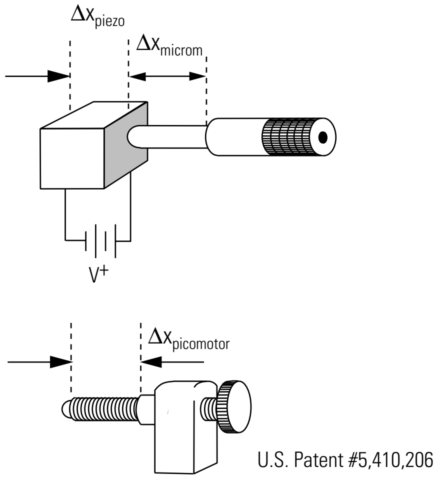


Figure 3: Comparison of a conventional piezo-driven actuator and a Picomotor. The conventional actuator's extension is the sum of the extensions of the piezoelectric material and the micrometer. In the Picomotor, the piezo is used only to turn the screw and not to hold the adjusted position, leading to greater stability.

Because the piezo is used only to turn the screw and not to hold the adjusted position, the Picomotor does not suffer from the typical piezo problems of hysteresis and creep, and can maintain its position with no applied voltage. However, a problem that conventional piezo-driven actuator and Picomotors do share is that of repeatability. Although the Picomotor does not exhibit hysteresis, small variations in screw rotation from step to step can lead to repeatability errors. These errors are accentuated if the force acting against the Picomotor's motion changes throughout its travel, as when moving against a spring.

Example: Wafer Height, Tip, and Tilt

The simplest application of the Picomotor is when it is running open-loop and the end-user makes all the adjustments. Such an example is when the Picomotor is used in semiconductor wafer processing and inspection equipment as the actuator for Z, tip, and tilt adjustment of a stage. (The tip and tilt can be automated given an external feedback loop.) Servo and stepper motors cannot be used in such an application because of their size and mass. They are too bulky to be placed on the high-speed scanning XY translation stage that moves the wafer or mask. The Picomotor's compact size and low mass allow it to be integrated directly into the moving translation system, as shown in Figure 4, providing compact yet stiff high-resolution adjustment support for the wafer chuck.

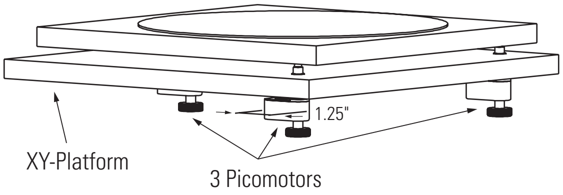


Figure 4: The high-speed translation stage uses three Picomotors to adjust the height, tip, and tilt.

While the wafer or sample is scanned for inspection by the fast XY stepper or servo system, the sample is supported by a set of three Picomotors that are adjusted for orientation and focal height. This adjustment is periodically updated and then held constant over significant time intervals. The three Picomotors are capable of setting positions to tens of nanometers and maintaining it to much better than 10 nm, even when no power is being applied. Because the Picomotors are also available in vacuum-compatible and non-magnetic versions, they can be used in sensitive electron-beam and UV-optics environments.

Example: Active Beam Stabilization

In another industrial application, the Picomotor has been used to counteract laser drift in metrology applications. Actively stabilizing the laser beam pointing leads to significant improvements in the metrology of the system. (Sampas and Anderson have also employed electronically actuated mirrors to automatically align and mode-match a laser beam to an optical resonator.[1])

Basically, the Picomotors are used in a system of two actively controlled mirror mounts to maintain pointing stability. The system, similar to one built by Grafström et al.[2], is shown in Figure 5. In this system, the laser beam exits from the laser itself and is reflected off two mirrors prior to reaching the work site. Each mirror mount has two Picomotor actuators, which are actively adjusted for beam stabilization. The beam pointing is held constant by adjusting the two mirror mounts, M1 and M2. The Picomotor's small size, high resolution, stiffness, and power-off locking make it an ideal actuator for adjusting the mirror mounts. Also, the Picomotor can be built to operate in an environment safe for sensitive UV optics.

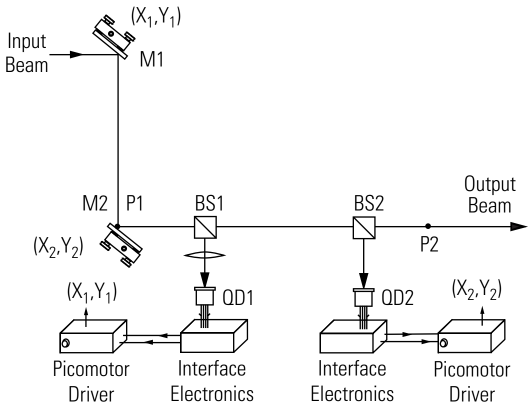


Figure 5: Beam stabilization application. QD1 images point P1 to control mirror mount M1. QD2 images point P2 to control mirror mount M2. Each of the system's sampled legs operates independently, provided P1 is sufficiently close to M2 and far from P2.

To sense the position of the laser beam, two beam splitters are inserted into the beam path. Each beam splitter directs a portion of that beam onto one of the quadrant detectors, QD1 or QD2. 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 that drive mirror M2 and keep the laser beam centered on P2. The two quadrant photodetectors act as the two reference points that define a line in space. By keeping P1 sufficiently close to M2 and far from P2, the sampled legs 1 and 2 can be treated independently and the two feedback loops can be kept independent of each other, greatly simplifying the feedback system.

Both quadrant photodetectors are oriented as shown in Figure 6.

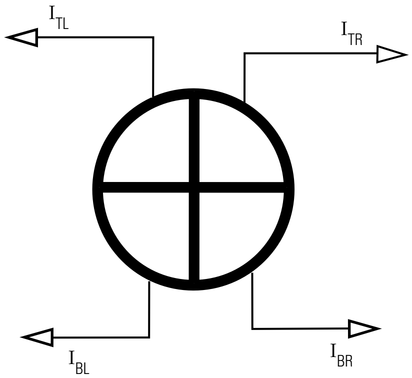


Figure 6: Alignment of the quadrant photodiode used to measure the position of the optical beams in Figure 5.

Quadrant detectors generate four photocurrents that are related to the portion of the optical beam that strikes each quadrant. The four photocurrents are sent to the interface electronics where they are individually amplified[3], as shown in Figure 7. 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 of the photocurrent amplifiers. One can simply choose the electronic gain such that the photodiode signal corresponds 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 (V_{UP}) and a left-minus-right signal (V_{LEFT}). For an optical beam nearly centered on the detector, the difference signals are directly proportional to the beam displacement from the detector's center.

The V_{UP} and V_{LEFT} error signals are used by the Picomotor driver to control the position of M1 and M2. Any misalignment of M1 or M2 with respect to the

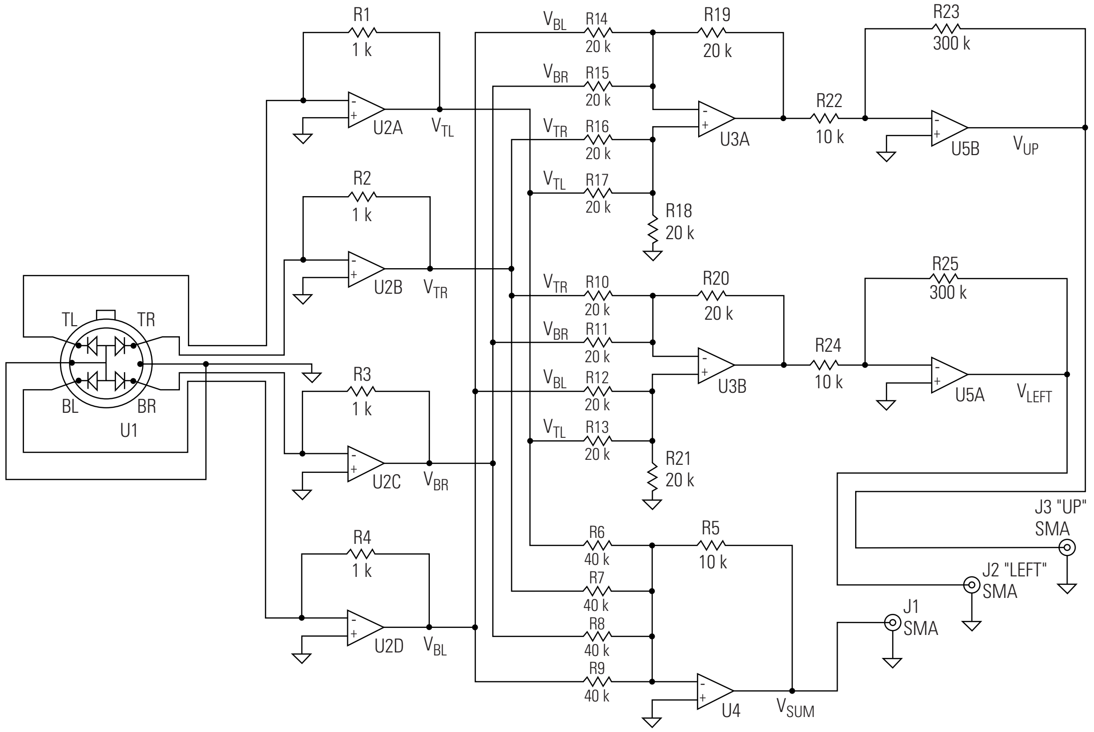


Figure 7: Photocurrent amplifiers. The four photocurrents from the quadrant photodetector are amplified and combined to produce vertical and horizontal error signals.

detector's center generates an error signal and hence a correction by the Picomotor driver. The geometric magnification of the system can be found in Figure 8.

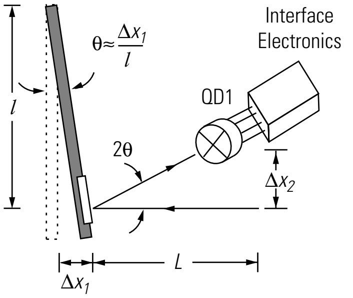


Figure 8: A derivation of the geometric expansion of the system shown in figure 5. A small Picomotor motion, Δx_1, results in a mirror deflection, $\theta \approx \Delta x_1/l$. The beam is then deflected by 2θ and the resulting displacement on the quadrant detector, Δx_2, is therefore $2L\Delta x_1/l$.

A small Picomotor motion Δx_1 results in a mirror deflection $\theta \approx \Delta x_1/l$, where l is the distance from the Picomotor to the rotation axis of the mirror mount (1.625" or 4.128 cm). The beam is thus deflected by 2θ and the resulting displacement on the quadrant detector, Δx_2, is therefore $2L\Delta x_1/l$, where L is the distance from the mirror to the quadrant detector. The geometric magnification is therefore $2L/l$. By having points P1 and P2 far from the mirror, this geometric magnification can be fairly large.

Since the Picomotor drivers have a threshold of 250 mV, the pointing error in an analog-control system such as this one is estimated by dividing the 250-mV threshold by the rest of the feedback-system gain. If the system gain is 30 (the differential gain of the error signals) times 1 V/mm (from the quadrant detector) times 97 (the geometric magnification of the legs $2L/l$, where l=1.625" (4.128 cm) and L= 2 m), the pointing error of the system would be 86 nm. That is, the 250-mV threshold will generate an uncertainty of the Picomotor of 86 nm in each direction. This is equivalent to an angular error on the order of 2 microradians. Of course, an alternative to this theoretical calculation is to measure the loop gain directly. Simply translating the Picomotor a known amount (100 pulses, for example) and measuring the resultant error voltage (V_{UP} or V_{LEFT}) will do the trick. If on the other hand, GPIB control is used, the pointing error in the system is related to

30 nm, the approximate step size of the Picomotor, and is similar to the quasi-analog system explained above. (Since the Picomotor takes 30-nm steps, the angular error is inherently limited to 30 nm/4.128 cm, or 0.7 microradians, for a pointing error of 1.4 microradians, independent of the geometric magnification or the electronic gain.) Circuit and geometry gain may result in measurement resolution that exceeds the actuator's step resolution. In such cases, the Picomotor will dither around the correct position until power is removed.

In applications where the active mirror control will be turned off during critical operation, the Picomotor's power-off stability makes for quiet operation. However, drift or vibrations that occur during power-off will not be canceled until power is re-established. For active drift/vibration cancellation or alignment, the Picomotor controller dynamics will come into play, with quite different behavior depending on whether the system is using analog or digital control.

In an analog control loop, the Picomotor driver pulse rate is proportional to the applied voltage, with a dead-band of ±250 mV. Thus, the analog voltage effectively controls the Picomotor velocity, while the measured position error relates to the Picomotor position. As long as the electronic bandwidth is wide enough, the motor will never overshoot, and will act as an overdamped system. When the system gain is set adequately high, a single tick of the motor will be enough to dither the controller into or out of its dead zone. If the gain is set too high, the motor can never sit quietly, and will dither in and out of the dead-band at about 10 Hz. The motor, acting as an integrator because its derivative is being controlled directly, will then be subject to windup due to overly sluggish response.

In a digital control loop, the decision to apply a Picomotor pulse is made by the user's circuitry, and therefore the dynamics can be set based on the application. Now, the full bandwidth of the motor is available directly to the user. In theory, this gives the user an actuator bandwidth of up to 2 kHz, a slew rate limitation of 1 microradian per 0.5 msec, and a resolution of 1 microradian. Digital control runs into the same kind of dead-zone problems as analog control if the gain is set so high that the measurement resolution exceeds the actuator resolution. One implementation for a digital control loop uses a sigma-delta a/d converter synchronized to the 60-Hz line so that you get data every 16 msec. With a reasonable algorithm, you can still keep significant bandwidth questions out of the way by estimating how far away you are and only sending out enough pulses to stay in range until the time of the next measurement.

Summary

Because of its unique features—30-nm resolution, exceptional long-term stability, and power-off locking—the Picomotor is ideal for set-and-hold applications as typically found in the optics and semiconductor industries. For instance, its compact size and low mass allow it to be integrated with high-speed scanning stages, like those in semiconductor wafer processing, and with inspection equipment. Moreover, the stability of the Picomotor makes it ideal for active beam-pointing systems. Special versions of the Picomotor—including vacuum compatible, UV compatible, non-magnetic, and tiny (0.5")—allow it to be used in special environments.

References

1. 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.

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

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

Patents

The Picomotor is protected by U.S. Patent #5,410,206.

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