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Piezo-Based Mechanisms Provide Necessary Precision Required for Laser Eye Surgery

Introduction
Piezo motion-based mechanisms deliver a range of features preferred in medical engineering and life science applications, such as lubricant-free drives and sterile ceramic designs. The non-magnetic nature of ceramics is an advantageous characteristic in high-energy scanning/imaging based on strong magnetic fields. Precise motion along with incredible speed can be achieved with piezo mechanisms.

The use of optical glass for vision defect correction has been successfully carried out since medieval times. The first clinical studies exploring the use of surgical methods to "shape" the cornea were initiated in the last century.

Laser technology
The arrival of laser technology has replaced the steel scalpel with high energy photons. Today, many different well-established laser methods are available that correspondingly influence the cornea’s curvature to correct visual acuity.

The common decisive factor in all these laser methods is the need for high-precision positioning systems to control and focus the laser beam. Piezo-based mechanisms are not only fast and reliable but are also capable of working with the necessary precision. Due to the availability of compact and different designs, piezo-based mechanisms can be easily integrated into today’s laser systems. Moreover, gimbal actuation is offered in a compact package.

Controlling a laser beam requires maximum precision. Piezo-based nanopositioning systems are ideal for all these applications.

The S-334 shown in the below picture is a compact piezo laser beam steering mirror unit. It has two orthogonal axes and a parallel kinematics design, which eliminates polarization rotation by allowing for a single pivot point.

Piezo advantage
Scanners must be optically conjugate. Extra optics are required between the scanners when two independent galvanometer scanners are used, further increasing complexity, aberrations, and losses.
Piezoelectric scanner tubes for endoscopy/bio-imaging of the eye

High-resolution two-photon endoscopy and microscopy use mini piezoelectric XY scanner tubes. In a recently published research paper, biological imaging of the eye using a two-dimensional fiber scanner-mechanism based on a bespoke, compact piezoelectric scanner tube with an outer diameter of 1.5mm is discussed in detail. The small instrument can be placed within a 2mm diameter, providing a spatial resolution down to 1.5μm.

Mini piezoelectric XY scanner tubes (left) and standard piezoelectric ring-shaped actuator.

Design of the two-photon excitation fluorescence endoscope. (a) shows the piezo scanner tube; the complete 2 photon probe is shown in (d). (Source: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3018080)
Piezo Flexure Actuators and Other Novel Piezo Mechanisms for Precision Motion Control Applications

Flexure-guided and motion-amplified actuators provide convenience and performance for the OEM designer. Piezo motors expand the motion range.

By Scott Jordan and Stefan Vorndran, PI (Physik Instrumente) L.P.

Piezo actuators, a special form of electro-ceramics, are the gold standard when it comes to precision, speed, and force in a small package. To make them more accessible for the OEM designer, manufacturers package the actuators inside an arrangement of flexures providing precision guidance and amplified motion along with a simple mounting interface. Flexures are usually made of aluminum, steel or titanium. With the absence of friction and wear, they can provide billions of cycles of maintenance-free service.

At the heart of piezoelectric flexure actuators is a stack of layers of specialized ceramic, only a few dozen microns thick, interleaved with electrodes, and sintered into a solid structure. The most common piezo ceramic for high-performance positioning applications is PZT (lead-zirconate-titanate), a ferroelectric ceramic. This material is useful for positioning because PZT ceramic exhibits a small, but almost linear dimensional change as voltage is applied across the electrodes. This provides a precise, controllable motion input to the engineer’s mechanism. Position changes on the order of nanometers can be achieved without difficulty.

Why Use Piezo?
The operation of the piezo ceramic element is characterized by four factors: a) precision; b) speed; c) short travels; and d) high force.
The stack’s positioning precision comes from its almost-linear dimensional change, which is free of stiction effects and can allow controllability down to the sub-nanometer range. This is why piezoelectric mechanisms are at the heart of today’s semiconductor lithography tools, atomic-force microscopes, and the other nanoscale-precision systems.

Its speed comes from the solid-state actuation of the stack, which propagates at the speed of sound through the material, yielding responsiveness into the kHz region, with correspondingly impressive force capability. The speed of sound actuation also means that piezo actuators can respond to an input in microseconds, a feature that makes them suitable to applications such as valve control and nano-dosing where nanometer precision is only infrequently of secondary importance.

Its travel limitation comes from the maximum strain the actuators can achieve, typically about 1 percent of their length. Consequently, piezoelectric flexure actuators utilize frictionless lever amplifiers that magnify the actuator motion. Clever design means motion ranges of up to 2mm can be achieved in compact packages.

Until recently, piezoelectric flexure actuators have mostly been employed inside specialized piezoelectric stages for ultra-precision positioning applications and were not easily available to the OEM mechanical engineer. That has changed, and flexure actuators with long travels are now available as off-the-shelf items for ready integration into custom mechanisms. This new accessibility has opened the door for a wide variety of specialized mechanisms across a broad spectrum of industries.

Animation – piezo flexure drives explained
Ease of Use and Cost Effectiveness

The latest generation multilayer piezo actuators are based on all-ceramic designs. They can handle high humidity environments, unlike their conventionally polymer insulated siblings.

Central to the utility of piezoelectric flexure actuators is their range of configurations and their well-thought-out mounting provisions. These are easy mechanisms to integrate into a design. Everything has been considered: their integrated preload mechanisms accommodate even high-dynamic actuation; their optional position sensors are pre-aligned and reproducible; their flexure guidance accommodates common applications without difficulty. A wide range of controllers are available, spanning the spectrum of capability and cost. Some feature the latest communications interfaces, internal waveform-generation capability, all-digital servo-controlled including trimpot-free calibration, and integrated data-collection options, all in cost-effective, OEM-friendly configurations.
Broad Choices, New Options
The new piezoelectric flexure actuators complement and extend the existing portfolio of form-factors and packaging styles for piezoelectric actuators. Ceramic stacks – with or without integrated position sensors – have traditionally been available to engineers wishing to perform all integration.

Packaged actuators have commonly been used for applications needing easy mounting and integral low-stiction preloads for dynamic actuation.

The new breed of fully integrated flexure actuators now offer preconfigured subassemblies which integrate stictionless lever amplification as well as preload elements and optional position feedback. Thus, piezoelectric flexure actuators offer especially easy mounting for the greatest convenience and performance for research and OEM applications, and they require the least specialized engineering to design-in and implement.

All of these choices share the common benefits of piezoelectric actuators, such as nanoscale precision, high speed and force, solid-state and lubricant-free actuation, non-magnetic and field-free operation, and vacuum compatibility.

Travel vs. Force Generation
Piezo flexure actuators are used for precision positioning, as well as for moving things quickly, and for force generation. Force generation usually means pushing against an external elastic material.

**Piezo flexure amplified actuators in different customization levels, from low-cost OEM actuators suited to drive micro-pumps to complete closed-loop nano-focus positioning systems.**

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**Travel vs. Force Generation**
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**Piezo flexure actuator with a simple parallelogram flexure guiding system and motion amplifier. The amplification r (transmission ratio) is given by (a+b)/a.**
As the diagram shows, working against a load reduces the available travel of an actuator, according to a simple formula:

\[ F_{\text{max eff}} \approx k_f \cdot \Delta L_0 \left( 1 - \frac{k_T}{k_T + k_s} \right) \]

Effective force that a piezo actuator can generate in a yielding restraint, where:

- \( L_0 \) = max. nominal displacement without external force or restraint (m)
- \( k_T \) = piezo actuator stiffness (N/m)
- \( k_s \) = stiffness of external spring (N/m)

**Stiffness, Responsiveness**

The additional motion provided by flexure-amplified piezo actuators does, however, come at a price. With increasing amplification ratio, both stiffness and responsiveness are reduced. Nevertheless, well designed piezo flexure actuators can still provide sub-millisecond step-and-settle times, significantly faster than any other conventional actuator.

The following relations apply to (ideal) motion amplifiers for any primary drive system:

\[ k_{\text{sys}} = \frac{k_0}{r^2} \quad \Delta L_{\text{sys}} = \Delta L_0 \cdot r \quad f_{\text{res-sys}} = \frac{f_{\text{res-0}}}{r} \]
In this formula:
\[ r = \text{motion amplifier ratio} \]
\[ L_0 = \text{travel of the primary drive} \ (m) \]
\[ L_{\text{sys}} = \text{travel of the lever-amplified system} \ (m) \]
\[ k_{\text{sys}} = \text{stiffness of the lever-amplified system} \ \text{(N/m)} \]
\[ k_0 = \text{stiffness of the primary drive system (piezo stack and joints)} \ \text{(N/m)} \]
\[ f_{\text{res}-0} = \text{resonant frequency of the primary drive system (piezo stack and joints)} \ \text{(Hz)} \]
\[ f_{\text{res}-\text{sys}} = \text{resonant frequency of the amplified system} \ \text{(Hz)} \]

Resonant frequency is directly proportional to the responsiveness of the system.

Custom Actuators: No One-Size-Fits-All Solution
With the variety of parameters, such as size, force, precision, travel range and cost, it is obvious that one flexure actuator cannot fit all applications. Often, a standard part may come close enough to be integrated in a prototype, however, for optimized cost and performance, it usually pays off for the OEM mechanical system engineer to work closely with an experienced piezo mechanism manufacturer. Prototypes of custom designs can be prepared within as little as a few weeks.

Custom flexure positioners in different sizes for different load and force generation. Piezo-flexure drives are used for applications from fiber-optics alignment to precision machining.

Mars Mission: 100 Billion Cycles of Lifetime
Regardless of the form-factor, the latest designs of piezoelectric actuators are very reliable mechanisms. They must be, since they are the mission-critical heart of so many industrial and research applications, ranging from semiconductor fabrication to atomic-force microscopy. After all, they are structurally quite similar to ceramic capacitors, which are ubiquitous in electronics. However, they can be sensitive to humidity. Previously, PZT stacks were encapsulated by painting them with a polymer coating. This provided a small amount of protection against infiltration by ambient water vapor. Far more effective is the patented construction of PICMA® model actuators – developed by Physik Instrumente (PI), which has played a pioneering role in advancing the
development of piezo devices – incorporating a hermetic ceramic coating and many subtle design details which ensure long life, even in the presence of high humidity. PICMA stacks are used in all PI flexure actuators.

The solid state, frictionless design means wear and tear is not an issue when it comes to lifetime. Recent tests for space qualification of PICMA actuators have shown that even after 100 billion cycles the actuator performance only dropped by a few percentage points. See [www.ncbi.nlm.nih.gov/pubmed/21507759](http://www.ncbi.nlm.nih.gov/pubmed/21507759).


**Expanding the Spectrum of Piezoelectric Motion**

Piezoelectric flexure actuators are but one utensil in a deep toolbox of motion technologies driven by piezoelectric principles, which include:

- Piezo ceramic stacks
- Packaged, preloaded stack piezo actuators
- Piezo flexure actuators
- Piezo linear motors with long travels and nanoscale position-hold stability
  - A. Walking motors for high push/pull and holding force
  - B. Ultrasonic resonant motors for high speeds
  - C. Incrementing inertial motors (stick/slip) for low cost and minimized dimensions

Different piezo motor driven actuators provide long travel ranges to 100’s of mm’s: inertia-type mini-rod actuators (top left), ultrasonic, high-speed actuator (top right) and Q-motion series miniaturized multi-axis stick-slip motor stages (bottom)
Comparison of force, speed, and travel capabilities of different piezo-based drive systems

Summary
Piezoelectric flexure drives offer unmatched ability to drop into a custom assembly and provide fast, precise actuation without fuss and bother, and with demonstrated reliability to extend into the many billions of cycles.

Recently-introduced piezo-motor technologies expand the use of piezo motion into long travel applications.

Piezoelectric devices are increasingly being utilized by product designers and incorporated successfully into a widening range of applications where precision motion control is needed. These devices are compact, require low voltage, deliver high torque, exhibit short response time, generate little heat, are both nonmagnetic and vacuum compatible, and have few mechanical component parts to wear out and service.

The latest generation of piezo mechanisms delivers an even broader product development capability for OEM designers.