Tiny motor helps designers pack more performance into smaller products

Patented piezoelectric design delivers high speed and force with low power use

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Piezoelectric motors are emerging as a powerful new force in miniature product design. One such device is the SQUIGGLE® motor, a linear piezoelectric motor from New Scale Technologies. The smallest SQUIGGLE motor (figure 1)measures only 1.55 X 1.55 x 6 mm and uses less than 400 mW to produce 20 grams of linear force at 5 mm per second [1]. Even less power is used at lower force and speed. The motor uses no power at all to hold a set position, which is important for battery-powered devices.

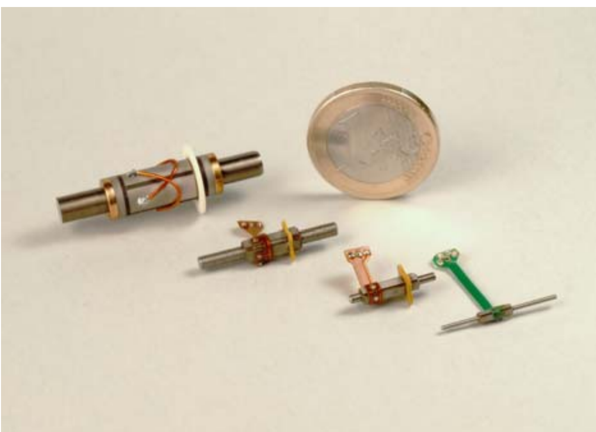

Figure 1. The smallest SQUIGGLE motor measures only 1.55 X 1.55 x 6 mm and uses less than 400 mW to produce 20 grams of linear force at 5 mm per second.

The combination of small size, low power use and high precision makes the SQUIGGLE motor interesting for applications including mobile phone cameras, electronic locks and latches, medical devices such as endoscope optics and drug pumps, and microfluidic devices including fuel cells and lab-on-a-chip devices.

Operating principle

The patented [2, 3] SQUIGGLE motor consists of four piezoelectric (PZT) plates bonded to a threaded metal tube, with a matching threaded screw (figure 2). The tip of this screw is used to push a load in a smooth, precise linear motion along the screw axis.

The PZT plates are bonded to flat surfaces on the outside of the metal tube at 90 degree spacing. The poling directions are aligned such that a common drive voltage on opposite pairs of plates produces opposing strain (figure 3). The opposing d_{31} strain is parallel to the plate surface and bends the nut. The bending strain is applied at a frequency matched to the first bending resonance frequency of the tube. At this mechanical resonant frequency a small PZT strain is amplified by the Q of the mechanical system. By symmetry the resonant frequency of the orthogonal PZT plate pairs is matched. The “hula hoop” or orbital vibration mode is created by generating PZT strain in orthogonal plate pairs at the resonant frequency with 90 degree phase shift. Both sinusoidal and square driving waves have been demonstrated.

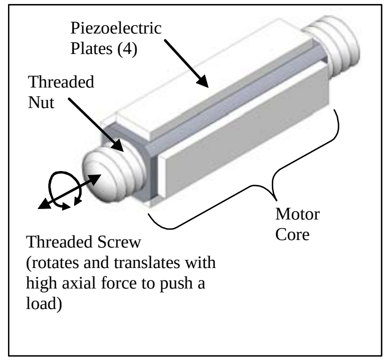

Figure 2. The SQUIGGLE motor is a simple design with very few parts and no gears

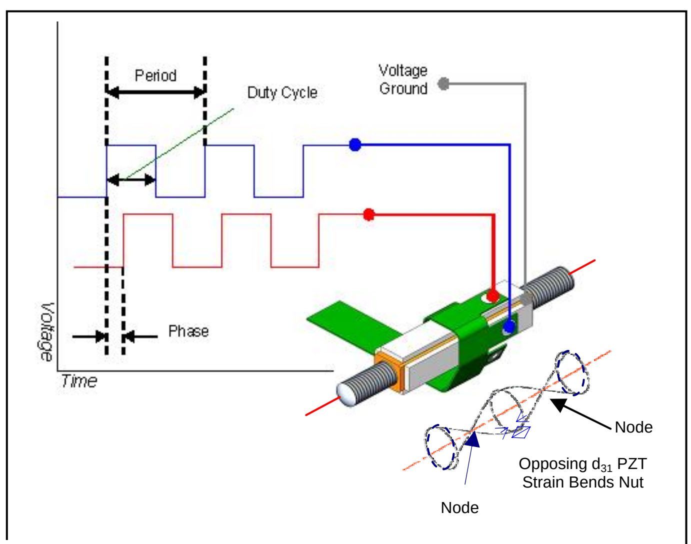

Figure 3. Opposing bending strain in orthogonal pairs of piezoelectric plates creates an orbital motion in a threaded nut, driving the matching screw with smooth linear motion.

Tangential friction force of the vibrating nut rotates and translates the screw. This unique operating principle “wraps” the vibration motion of the nut around the screw threads to produce direct linear movement without additional mechanical conversion. The thread friction is not parasitic, but directly drives the screw. The threads multiply linear force and position resolution.

The highest efficiency of mechanical coupling between the tube and the screw is achieved at the ultrasonic frequency matching the first bending resonant frequency of the tube; approximately 100 - 150 KHz for the SQL Series SQUIGGLE motors. A light axial preload ensures constant contact between the nut and screw threads for best performance.

System integration

SQUIGGLE motors have excellent position resolution: users can signal the motor to move very small distances. The smallest SQL series motors have resolution of 0.5 microns, while the larger SQ-100 motors have resolution of 20 nm. However, the motor speed varies with applied load and device friction. Therefore a closed-loop control system is recommended for applications that require absolute position, repeatable positioning, or precise speed.

In a closed-loop positioning system, a sensor detects the actual position and feeds the information to the motor controller. The controller compares actual position to desired position, and moves the motor to correct any error. This allows the motor to reach a precisely controlled position. Similarly, controlled speed is achieved by adjusting the driver gain to minimize the difference between the required position and the actual position at regular time intervals.

Position sensor choices range from miniature optical encoders to simple limit switches. Choose an option with resolution and travel range to fit your application [4]. SQUIGGLE motors have

Position resolution is determined by three factors: the resolution of the position sensor, the resolution of the motor, and the A/D converter in the controller. If position accuracy of 10 microns is needed, the position sensor must have a resolution of 5 microns or better, the motor must have a position resolution of 2.5 microns, and the A/D converter must be capable of resolving the feedback signal into small enough increments to allow signals to the motor at its best resolution.

For example, consider a system requiring 10 microns resolution over a range of 2 mm. A possible solution is a Hall Effect sensor with a magnetic strip 4 mm long (using the more linear center of the magnet and avoiding the last mm on each end). A 10-bit A/D converter will supply resolution of 0.001 of the 4 mm, or 4 microns. The SQL Series SQUIGGLE motor resolution is 0.5 microns, so the limiting factor is the A/D converter. Assuming some background noise, this will still be enough sensor resolution to achieve 10 microns repeatability. With a higher resolution A/D chip, the position resolution would be better.

Numerous closed loop systems using SQUIGGLE motors have been demonstrated, including the phone camera lens assembly and the lock modules described in the next section, as well as closed-loop positioning stages with resolution of 0.02 microns.

Controllers

SQUIGGLE motor controllers produce the two-phase ultrasonic signals to drive the SQUIGGLE motors. They accept an analog or digital quadrature (RS-422) signal from a position sensor to provide closed-loop operation. The software provided allows the user to define the range and resolution, which are then used in the positioning commands. The electronics use PID (Proportional, Integral and Derivative) controls to actively tune the response of the motor to the feedback signal. These coefficients are interactive and work to keep the motor speed from leading, lagging or oscillating with respect to the sensor feedback signal. The controllers can also be used in open-loop mode.

Motor control software is compatible with Windows XP and Vista. An ActiveX control may be integrated into other applications written in languages such as C++ or Visual Basic. Documentation lists the low-level ASCII control codes that an embedded system or microcontroller would send to a motor control chip.

Input parameters for ICs capable of generating square waves to drive the motor are shown in the table.

Parameter	Description	Value for SQUIGGLE motor
Period	The time between the start of each cycle. The inverse of frequency.	Must match or be near the period of the mechanical resonance of the tube.
Duty cycle	The time that the drive signal is high within each cycle	No more than 50% of the period
Phase	The separation in time between the start of a cycle in each drive signal	25% of the period
Amplitude	The maximum voltage achieved at each cycle	Up to 200 V

The smallest SQUIGGLE motors use a direct linear drive providing 20 to 40 V. For the larger motors, a resonant amplifier circuit is added to boost the output from the IC to 100 to 200 V. This circuit also improves efficiency by storing unused power in inductors for the next cycle. The inductors are matched to the specific capacitance of each size motor.

The IC should be able to generate square waves with a programmable phase shift. If not, a phase shift may be created by generating three square wave signals and combining two of them with an XOR gate.

Voltage (amplitude) mode control

In controller implementations where the output voltage has a wide range, the speed of the motor can be controlled by varying the voltage of a continuous drive signal. Voltage control has the advantage of providing quieter motion, but is appropriate only when a position sensor and PID control loop is available. In open-loop applications, burst mode provides the most predictable performance.

Burst mode control

In controller implementations where the output voltage is fixed or the selectable voltage range is limited, the speed of the motor can be controlled by sending bursts of drive signals at regular intervals. The burst duration within each interval determines the motor speed.

Some ICs are programmable as to the number of pulses to issue to the motor. With these, a single timer is needed to restart the motor after each interval. With ICs that do not support a pulse count, a pair of timers must be established. One timer turns the motor on at each interval. The other timer turns it off after the burst duration has elapsed.

In closed-loop applications, the PID loop is the interval timer. At each interval, the PID control firmware checks the position of the motor and calculates the appropriate number of pulses to issue (or burst duration) based on the position error and the PID coefficients. The number of pulses varies directly with the position error.

Calibrating open loop resolution

As described previously, a position sensor and closed-loop operation are recommended where step size, position repeatability and/or velocity control are important. If open-loop operation is used, it is possible to calibrate an average step size for a given motor and mount. The average step size, for example, is the number of pulses required to move 10 microns. It must be emphasized that this is an average, and each individual step may vary by as much as ± one step.

One method of calibration involves a capacitance gauge. For each direction of motion (with and against the load), the motor is moved to a start position and a baseline capacitance is recorded. The motor is then sent numerous bursts of 100, 200, 500 and 1000 pulses. After each burst, the capacitance is recorded. Using theses results, the average distance moved may be calculated for 100, 200, 500 and 1000 pulses. A curve may be fitted to these results, from which a required number of pulses may be computed for the desired step size.

Applications

Mobile Phone Cameras

Mobile handset makers are pushing for phone cameras with better image quality. One approach is to replace fixed optics with a moving micro-lens assembly for auto focus and optical zoom. Lens modules using SQUIGGLE motors are small enough to fit into the mobile handsets, and use drive circuits that can be powered by a 3 V phone battery. The motors are silent, operate over a wide temperature range, withstand high shock, and require no grease or other lubrication that can contaminate the optics.

Two SQUIGGLE module reference designs have been developed for the phone camera market. Figure 4 shows an auto focus module in a SMIA85 package, using a SQUIGGLE motor to move a lens in a flexure guide. Figure 5 shows an auto focus / 3x optical zoom module that uses two SQUIGGLE motors to move two lens groups: one for auto focus and one for optical zoom. The lens groups are mounted on rails for smooth motion. Integral position sensors provide closed-loop control.

A commercial zoom module using SQUIGGLE motors was introduced by Tamron Co. Ltd. in February 2007 [5].

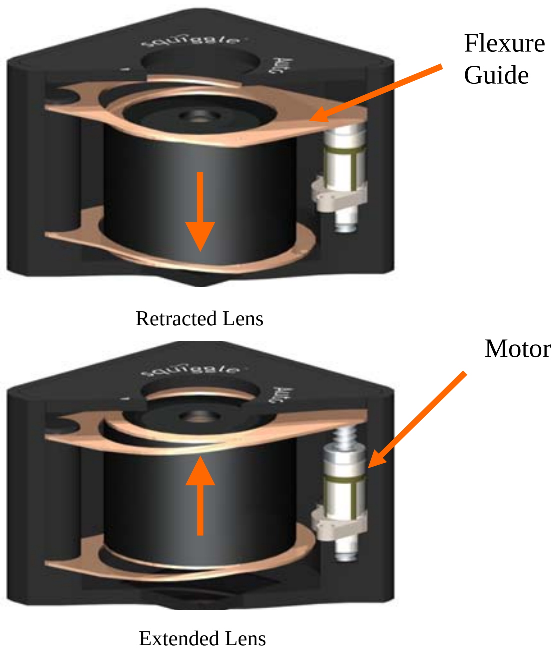

Figure 4. SQUIGGLE motor auto focus camera module in a SMIA85 package (8.5 x 8.5 x 6.1 mm)

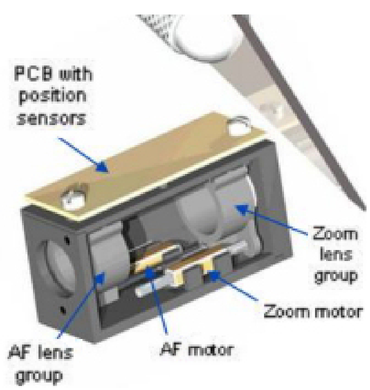

Figure 5. Auto focus and 3x optical zoom module using two SQUIGGLE motors is 8 x 12 mm. The height is determined by the lens design.

Electronic access systems such as magnetic cards, key panels and biometric sensors are replacing mechanical lock-and-key systems in many commercial and government facilities. The market for electronic access control systems is set to reach $6.1 billion by 2010, according to a report by Global Industry Analysts Inc. [6]. Electronic access improves security, provides better monitoring and flexibility, and reduces total system cost. In addition, electronic locks and latches are increasingly of interest for applications such as pharmaceutical cabinets and carts in hospitals, safety interlocks in automotive applications, and protective interlocks on IT hardware.

A new low-power actuator using a SQUIGGLE motor allows lock manufacturers to reduce the size and power requirements of their electronic locks and latches (figure 6). The actuator assembly integrates a SQUIGGLE motor and optical limit switches in a compact polymer housing. In a typical lock application, the tip of the SQUIGGLE motor screw pushes a spring-loaded shear pin, which engages the latching mechanism.

This actuator draws far less power and occupies half the space of solenoid or stepper motor mechanisms currently used in electronic locks and latches. The SQUIGGLE motor provides four millimeters of stroke with high force and speed, and holds its position with power off. It is controlled by a TTL driver card that runs on two standard AA batteries.

Medical devices

SQUIGGLE motors can be used to move focusing optics in an endoscope, using techniques similar to the phone camera application. This innovation dramatically improves a surgeon’s ability to view the target area by simply adjusting the focus, rather than attempting to reposition the entire endoscope.

The SQUIGGLE motor generates no magnetic fields in operation, and can be constructed entirely of non-ferromagnetic materials such as stainless steel, bronze and titanium. Such a specially-constructed SQUIGGLE motor can be safely used in and around magnetic resonance imaging (MRI) systems. An MRI-compatible drug pump system has been demonstrated by researchers at Roswell Park Cancer Institute in Buffalo, NY [7]. This syringe pump delivers drugs to animals being imaged in a 1.5 Tesla magnetic field. Several inches of travel are needed with 5 N of force to push a standard syringe with 1 to 3 ml capacity and achieve doses of 0.1 ml.

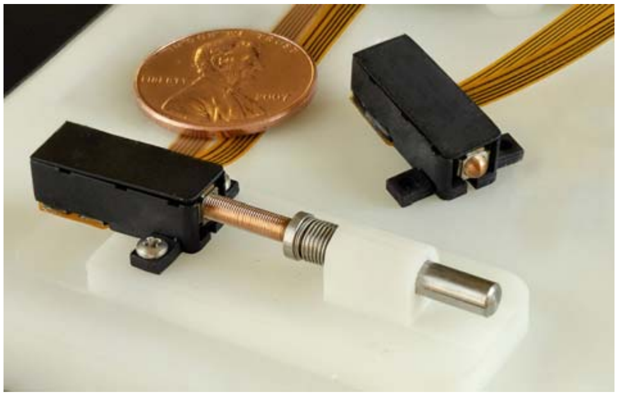

Figure 6. SQUIGGLE motor lock module, shown pushing a spring-loaded shear pin

In addition, the motor's small size and high-resolution motion promises to make wearable devices, such as insulin pumps, smaller and more comfortable. A design concept for a wearable drug pump uses the SQUIGGLE motor's drive screw to directly push a syringe. The motor produces tiny steps, at speeds of micrometers per minute to micrometers per hour, for basal and bolus drug delivery. An optional magnetic rotary encoder measures each step with sub-micrometer accuracy for 0.01 unit dosage control. The same motor moves at millimeters per second for reservoir replacement and priming.

Fluid control

Micro pumps are designed to move microliter and nanoliter volumes of fluid in a precisely controlled manner. A current hot application is the lab-on-a-chip system, which requires moving extremely small fluid volumes though a single chip to perform laboratory functions such as blood analysis or contaminant detection.

Other microfluidic applications include micro fuel cells, IC cooling, micro lubrication systems (using a fine mist rather than a flood of lubricant to reduce waste and pollution), and spacecraft thrusters.

Most micro pumps today employ flexing diaphragms and peristaltic motion [8, 9] which creates pulses of uneven pressure. Moreover, flow precision depends on the backpressure. A micro pump design [10] based on SQUIGGLE motors overcomes these limitations, by using the motor's precise linear motion to directly move a reciprocating piston or bellows (Figure 7). This positive displacement pump design enables higher precision, pressure and flow in a package that is one tenth the size of existing micro pumps.

The pump uses two linear motors and two pistons or syringes. The speed and location of the pistons directly determines the flow rate and volume. The two motors are operated in opposite phase to achieve continuous output flow: as one piston is filling, the other is emptying. Spring-loaded check valves in a manifold switch the flow when the motors reverse direction.

Unlike diaphragm pumps, the volume in each piston stroke is much bigger than losses in the check valves. This insures robust operation even with air bubbles or particles. This design also offers wide dynamic range: it can be used at high pressure and flow, or it can be used to accurately dispense nanoliters over many days or weeks. Closed-loop position control insures accurate flow control independent of back pressure. Finally, the operating frequency is less than one Hertz, which is virtually silent and minimizes pressure pulses. The size of this design is less than 28 X 6 X 3 mm, or 450 cubic millimeters.

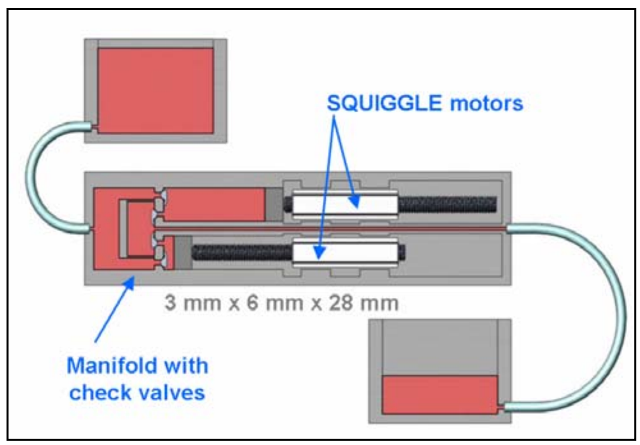

Figure 7. Positive displacement micro pump with SQUIGGLE motors enables higher precision, pressure and flow in a package that is one tenth the size of existing micro pumps.

Cryogenic applications

Specially constructed SQUIGGLE motors have been shown to operate at cryogenic temperatures. The motor is unique in that it can operate over the full temperature spectrum, from room temperature to cryogenic temperatures. It uses little power when moving and no power when stationery, and has low mass, so that it has low impact on the ability to cool the cryostat cooling. It also offers long travel in a very small package, which is important since space inside a cryostat is generally quite limited. This is especially true for portable cryogenic devices such as infrared imagers.

Until now, there have been few options for alignment of cooled optics in cryogenic sensors. A mechanical pass-through into the cooled chamber creates an unacceptable thermal load. Few electrical actuators that work at cryogenic temperatures have sufficient push force and travel distance to move optics. Conventional motors can not be used: the grease requireed to lubricate the gears, couplings and shafts freezes solid in a cryogenic cooler. Even if the lubrication requirement could be eliminated, the challenge of matching the thermal expansion properties of complex gear mechanisms is insurmountable. In contrast, the piezoelectric motor uses no lubricants and has few parts, which can be more easily assembled using materials with matched thermal expansion properties.

Two applications of cryogenic SQUIGGLE motors have been demonstrated. An SQ-100C SQUIGGLE motor has been demonstrated at 6 Kelvins in an experimental cryostat setup at the University of Sussex [11]. A custom build SQL series motor has been demonstrated to align optics in a portable cryogenic sensor for a hyperspectral imaging application [12].

Other applications

The SQUIGGLE motor has been used for several years as a precision nanopositioning tool in laboratory research applications, due to its high precision. Many other potential applications are emerging, in consumer electronics and industrial imaging as well as aerospace and defense. For example, designers of toys such as model trains, airplanes and robots are interested in the small, light-weight motor as it becomes available in high volumes. Industrial applications include improving barcode scanners by addition of focusing optics. Aerospace and defense applications include infrared imaging, laser system alignment and un-manned aerial vehicles. The potential for this tiny motor to add new performance to a wide range of systems is just beginning.

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[3] *Henderson, D. and Viggiano III,* D: Mechanism Comprised of Ultrasonic Lead Screw Motor. US Patent 7170214, January 2007

[4] New Scale Technologies: Application note, Choosing Positioning Sensors for SQUIGGLE Motors, 2007 (http://www.newscaletech.com/app_notes/position_sensors.html)

[5] Tamron Co.: Tamron Announces an AF 3X Zoom Lens Module in a Remarkably Compact Package with SQUIGGLE Piezo Ceramic Motors, February 14, 2007 (http://www.tamron.co.jp/en/news/release_2007/0214.html)

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[10] *Henderson, D.;* Novel Piezo Motor Enables Positive Displacement Microfluidic Pump. *Technical Proceedings of the 2007 Nanotechnology Conference and Trade Show, Volume 1-4*

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[12] New Scale Technologies: Application note, Use of Cryogenic SQUIGGLE Motors for Active Alignment of Cooled Optics in Cryogenic Sensor Applications, March 2007 (http://www.newscaletech.com/app_notes/hyperspectral.html)