TECHNICAL COMMUNICATION

NEW ULTRASONIC PIEZOELECTRIC ROTARY MOTOR PROVIDES SUPERIOR RESOLUTION AND DYNAMIC RANGE COMPARED TO CONVENTIONAL ELECTROMAGNETIC MOTORS

Accurate angular positioning with fast response is extremely important in many hi-tech and industrial applications. The heart of all automated angular positioning devices is a rotary motor, and the most common motor used is the conventional electromagnetic (EM) motor. Examples of such motors are stepper motors, vector and/or DC servomotors. In this paper we discuss a novel, low voltage, high torque, rotary motor, which uses piezoelectric principles rather than EM, and identify some of the limitations of EM motor systems, that it overcomes. The superior performance characteristics of the new piezomotor over the EM based system yields significant advantages in stabilized platform applications where high resolution, short response time, smoothness of motion and low drift are important.

Limitations of electromagnetic (EM) motors used in angular positioning

Some of the most important limitations of EM stepper motors can be summarized as follows:

- ***Low angular resolution*** — Angular resolution is fixed by the number of steps (increments) per complete revolution. For EM stepper motors this is typically limited to about 500 steps/revolution.
- ***Backlash and drift limitations*** — Need for a gear train to increase angular resolution magnifies backlash and drift problems.
- ***Slow response –*** Slow response arising from intrinsically highly inductive input impedance.
- ***Non-smooth motion*** – Intrinsic non-smooth stepper action motion is magnified at low speed with an increasing risk of stall.
- ***Load dependant Performance*** - Performance is vulnerable to changes in load, particularly in the absence of positional feedback mechanisms.
- ***Need for continuous power*** – Require continuous power dissipation even when stationary (i.e. in a braked position).
- ***Loss of Tracking.*** Risk of loss of the tracking-demanded position whenever the load exceeds the motor torque rating.
- ***Motor burnout*** – Risk of motor burnout if the motor is jammed physically whilst a continuous demand for movement is present.

Positioning control systems, using either servo or flux vector motors, partially compensate for some of the disadvantages of stepper motors, with some models having greatly increased angular resolution (e.g. 4000 steps per revolution). In these systems both position and angular speed are measured via an encoder and corrections also made for any system overshoot. This provides for increased angular resolution without the need for additional gearing. However, one significant drawback of both vector and servo motors is that they must continuously "hunt" to stay at their desired position. This means that they rely on continuously sensing small positional errors to generate the required correction demands necessary to hold the system locked on the target. Accordingly, the dynamic response of these systems is invariably limited by sensor noise, motor inertia, inductance and the motor drive technology.

Vector motors also use encoder feedback for position tracking. However, the primary difference between a vector motor and a servomotor (other than the electrical difference) is the intrinsic inertia of the vector motor's rotor. Vector motors use a variation of the standard squirrel cage rotor, consisting of steel laminations and aluminum or copper bars, which add mass to the rotor. Generally, they also have a larger diameter rotor than that of a servomotor. Both these factors increase the moment of inertia of a vector motor, which in turn limits its possible acceleration. This results in a limited range for the dynamic response.

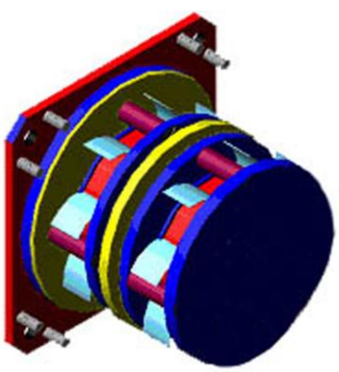
Stick-Slip

The ***Stick-Slip*** effect is another major factor limiting the accuracy and resolution of all EM based motors. When a driving force is applied to the motor, movement from rest is slightly delayed on the applied force. Initially, with finite force applied, there is no movement (Stick) until the force exceeds the system's static friction. At this point, there is a jump in position, which causes a small over-shoot (Slip). Thereafter, the force to maintain motion against the resistance of the friction during motion (dynamic friction) is less than that needed to start it. This arises because the coefficient of dynamic friction is less than the coefficient of static friction in the motor.

The Stick/Slip effect imposes limitations on angular resolution, speed of response and tolerable overshoot. As a result, manufacturers of EM motors are forced to employ transmission systems with high gear ratios. In theory these should deal with the angular resolution degradation, but this is only done at the expense of increased hysteresis and backlash, which are inherent in gear train mechanisms. The consequence is an absolute positioning accuracy several orders of magnitude worse than the system's theoretical resolution.

New rotary piezomotor technology

The pressing need for a new class of rotary motor that overcomes the limitations and disadvantages inherent in conventional EM-based motors has recently been met with the development by Discovery Technology International (DTI) of a novel range of low voltage high torque rotary motors based on entirely different (non-EM) electrical principles. The new piezomotor uses ultrasonic piezoelectric technology integrated with a platform that is controlled using either digital or analog controllers. These features provide a simplified design in which a gear-head/gearbox can be eliminated altogether. Many additional benefits are available because of the piezomotor's unique start-stop and ultra-fast response time characteristics.



Schematic illustration of new piezomotor (bi-directional configuration)

DTI Piezomotor Model # PM22RS (50 mm)

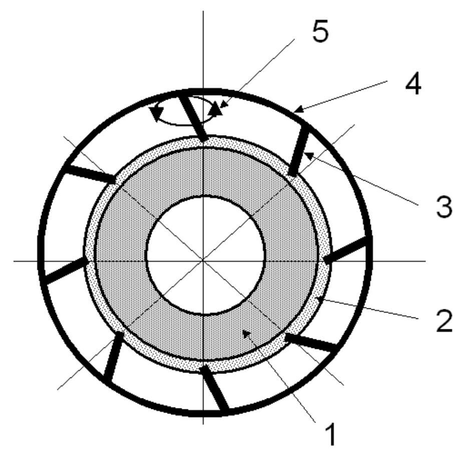
DTI's unique piezomotor technology provides performance superior to conventional EM motor-based systems in certain applications. These benefits include micro-radian resolution and accuracy, extremely low hysteresis and almost zero backlash. Its response is several orders of magnitude better for comparable motors. Furthermore, the new piezomotor system also addresses the key disadvantages of conventional piezoelectric-based actuator systems, which typically require high voltage (HV) power sources as well as HV linear power amplifiers. None of these drawbacks are present in the new piezomotor systems, which are designed to operate from a low voltage (e.g. <12 V DC). Also no electrical power is required to hold (lock) the system at any fixed position.

Piezo Rhino™ and Piezo Beetle™ series

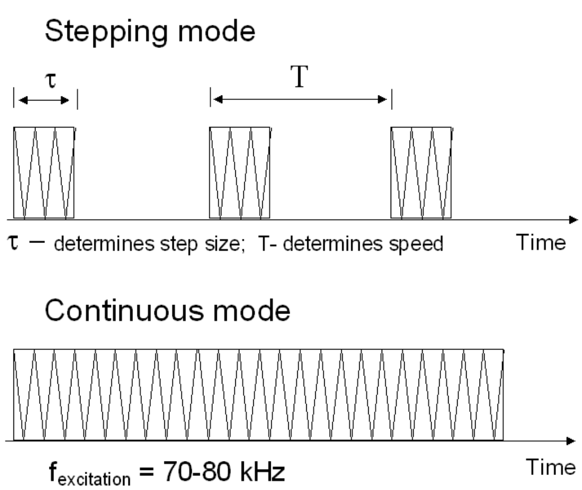
DTI's ultrasonic piezoelectric rotary motors are divided into two types depending on size and design construction; these are referred to commercially as the ***Piezo Rhino™*** *and* ***Piezo Beetle™*** series (see Table 3). The Piezo Rhino™ type, incorporate a unique combined rotary piezoresonator technology enabling a substantial increase in the coupling efficiency between the stator and the rotor. This, added to the fact that the piezomotor is a resonance motor, substantially increases the overall motor efficiency, providing simultaneously superior resolution and torque.
The Piezo Beetle™ type (patent pending) is a miniature (i.e. <20 mm O.D.) ultrasonic piezomotor. This type of motor is based on a single composite piezoelement-pusher component utilizing a novel excitation method in which bidirectional rotation is achieved using a relatively simple and compact design.

Principle of operation -

DTI' s piezomotors are of the ultrasonic standing wave type. They work on the principal of excitation of ultrasonic standing wave(s) within a piezoelectric resonator. A schematic of one of DTI's ultrasonic motors with piezoelectric ring resonator (**1**) and stainless steel pushers (**3**) is shown in the figure. Pushers (**3**) are attached to the piezoresonator through a vibrational shell (**2**). An ultrasonic radial standing wave is excited in the resonator causing the ring to expand and contract in radial direction, stimulating movement of the pushers along the radius. Because of their elasticity, the pushers vibrate with the same frequency, although phase shifted, in a direction orthogonal to the radius of the ring. The superposition of the two orthogonal movements results in elliptical movements (**5**) of the pushers. Because the pushers are held pressed against the rotor (**4**), their movement, via friction at the pusher contact area, causes rotation of the rotor.



Schematic of the piezomotor (*Piezo Rhino™* series). 1 – piezoelement (stator); 2 – vibrational shell; 3 – metal pushers; 4 – rotor; 5 - curve illustrating the elliptical movement of the tip of the pusher (amplitude exaggerated)

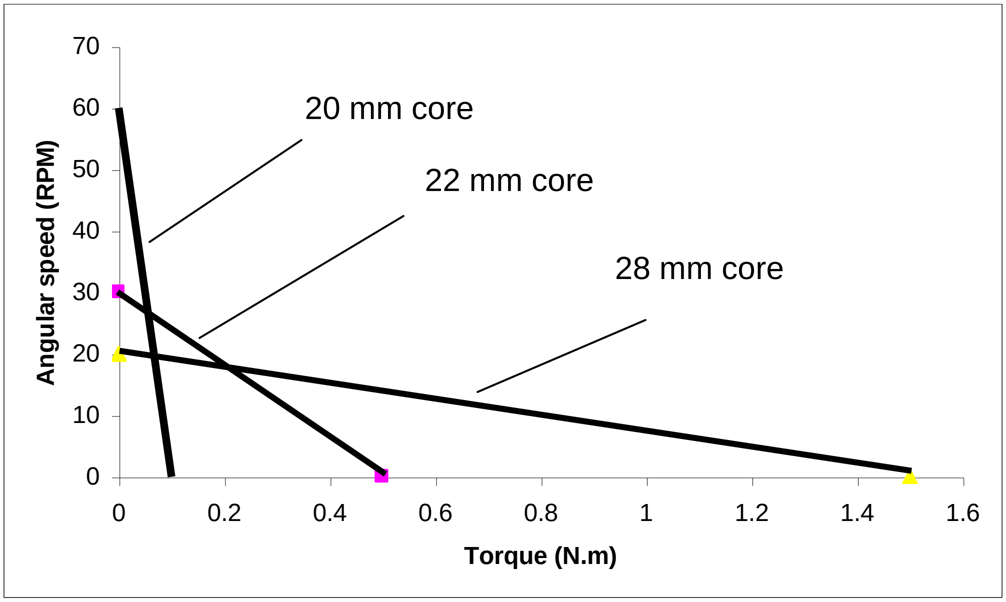


Digital control of the DTI's Piezomotor by Pulse Width Modulation (PWM)

The piezomotor is controlled by a train of electrical pulses supplied by a digitally controlled AC voltage source to the piezoelement. For the duration of each pulse the excitation AC voltage is applied to the piezoelement at its ultrasonic resonant frequency. The speed of the motor is altered by varying either the repetition rate of the pulses comprising the train or the duration of each individual pulse (i.e the pulses of excitation from the voltage source are modulated). This is achieved using a digital controller.

The waveform shown illustrates the basic principle of control in both stepping and continuous modes of operation. Digital control enables any movement from a **single sub-arcsec angular step to continuous motion** to be set up accurately and repeatably.

In conventional EM motors/gear systems, the unavoidable mechanical tolerances of traditional transmission systems are the single most important cause of degradation of positioning accuracy. The inherent high torque and resolution of the DTI piezomotor eliminate the need for a supplementary transmission/gearing system, so avoiding the usual backlash effects that limit accurate tracking. Indeed, the relationship between angular speed and motor torque obtained with three different size models of the new piezomotor is illustrated in the graph.



Load characteristics of three piezomotors with different angular piezo-ceramic core sizes (diameter of core as indicated)

The new piezomotor offers intrinsically superior dynamic performance and tracking bandwidth without the usual drawbacks of significant hysteresis, drift, and without the need for a HV power supply and linear amplifier. Older available piezo actuator-based systems albeit demonstrating faster response than stepper or servomotors, with a bandwidth typically above 1 kHz (as opposed to tens of Hz in most advanced servo motor systems), have other drawbacks, which are not present in the new piezomotor technology. The key beneficial characteristics of the new piezomotor compared to a traditional EM motor can be summarized as follows (see also Tables 1 & 2):

Key Benefits of New Ultrasonic Piezomotor

- ***Direct-Drive mechanism* -** Elimination of a mechanical transmission/gear system virtually abolishes backlash and hysteresis and provides better accuracy, repeatability and resolution.
- ***Elimination of the "Stick-Slip" effect* –** Elimination of "Stick-Slip" effect coupled with unique start-stop characteristics, removes one of the major limitations on angular resolution..
- ***High torque with wide range of torques* -** Initial high torque (and order of magnitude better than any comparable stepper motor) enables high dynamic (start-stop) characteristics. Wide range of torques (e.g. from 2 mN.m up to 6 N.m.) addresses many application requirements.
- ***Low temporal drift* -** Angular position of the rotor is held fixed (self-braked) by the self-decelerating torque of the motor. The same force "locks" the drive system of the motor, providing negligible angular drift (i.e. <1 arc-sec/hour).
- ***High resolution and high accuracy* –** High resolution (<1 arc-sec), with an absolute positioning accuracy of 4 arc-secs in closed loop mode (using a high-resolution optical encoder). The angular positioning accuracy is one order of magnitude better than the best of currently available systems.

- ***Rapid response, dynamic range of 3 kHz –*** Capacitive input impedance (i.e. capacity nano-farads) of piezomotor compared to inductive input impedance of EM motors (i.e. milli-henries) results in rapid response time (e.g. *10-50 µs*) several orders of magnitude faster than a comparable EM motor.
- ***Wide range of angular steps and angular velocities -*** Angular motion with steps ranging from less than 1 arc sec to continuous movement, covering a velocity range of 6 orders of magnitude (e.g. <5 µrad/s to >2.1 rad /s).
- ***Simplified power requirements –*** Controller system operates from low voltage (e.g. <12 VDC), enabling field deployment (e.g. airborne applications - where weight, size and reliability are critical).
- ***High Load capacity -*** High load capacity assures adequate performance at nominal loads
- ***Electromagnetic compatibility –*** Immunity to electromagnetic interference overcomes problems associated with using EM motors in applications, such as MRI and other similar environments.
- ***No risk of motor burnout -*** Burnout will not occur even if the motor is jammed physically whilst a continuous demand for movement is present.

Parameter	**Equivalent EM Stepper Motor**	**Piezomotor (Model PM-22R)**
Positioner applications	Requires angular step reducer	Direct drive
Rotational Range	360º	360º
Design Resolution (no step reducer)	525 µrad (0.03º = 108 arc-sec)	<2.4 µrad (.5 arc-sec)
Min. Controlled Angular Increment	525 µrad (0.03º = 108 arc-sec)	<4.8 µrad (1 arc-sec) With encoder (model; PM-22RS)
Backlash	0.1 – 1 of minimum increment	None
Hysteresis	Not available	<4.8 µrad (1 arc-sec)
Max. Speed	628 rad/s (6000 rpm)	3.14 rad/s (30 rpm)
Max.Torque	0.1 Nm	0.5 Nm
Self-braking Torque	Not available	0.51 Nm
Response Time	10 ms	10-50 µs
Demand - to Max. Speed	100 ms	0.3 ms
Velocity Range (Stepped-Continuous)	500 µrad/s to 20 rad/s with micro-stepping	5 µrad/s to 3.14 rad/s Defined by the controller
Reversal Time at Max. Velocity	100 ms	500 µs
Dynamic Range Bandwidth	100 Hz	2 kHz
Rotor Moment of Inertia	2.0×10^{-5} kg-m^2	$0.7/2.0 \times 10^{-5}$ kg-m^2
Load Capacity	20 kg	20 kg
Supply Voltage	12 VDC	12 VDC
Max. Power Consumption	10 W	6-8 W
Nominal Power Consumption	6 W	5 W
Mass	0.6 kg	0.2 kg
Dimensions	50 x 55 mm	50 x 50 mm
Long Term Drift (@20 C)	Not available	< 4.8 µrad/hour (1 arc-sec/hour)
Controller	Analog	Analog or Digital

Table 1. Comparison of key technical parameters of a typical piezomotor PM22RS) with a comparable size stepper motor.

Parameter/property	**Stepper motor**	**Piezomotor**
Type	Electromagnetic	Non-electromagnetic, PZT core
Angular resolution	Inadequate where high resolution required	2 to3 orders of magnitude superior than stepper motor
Backlash, hysteresis	Transmission/Gear system makes these significant at high resolution	Negligible
How the torque is applied?	Elastic, by electromagnetic force	Rigid, by friction force
Response time	Slow	2-3 orders of magnitude superior than stepper motors
Torque and dissipated energy when stopped	Applying braking torque require power consumption and heat dissipation when motor is static	Self-braking with max torque does not require power consumption and heat dissipation when motor is static
Jamming	Motor can overheat if jammed	Motor is not damaged if jammed
Power outage	Unpredictable with loss of track and position	Motor stops and holds position
Special applications	No MRI compatibility No EM pulse protection possible	Custom motor can be made: MRI-compatible; EM pulse prone

Table 2. Key differences - new piezomotor and a comparable size stepper motor.

Piezomotor Type*	**Piezo Rhino™**					**Piezo Beetle™**
Motor Model	**PM-20RS**	**PM-22RS**	**PM-46**	**UPM-20**	**UPM-22**	**PM-8R/PM-10R**
Mode of operation**	Cont/Step	Cont/Step		Cont/Step	Cont/Step	Cont/Step
Uni/Bi-directional	Bi	Bi	Uni	Uni	Uni	Bi
Max torque (N.m.)	0.1	0.5	6	0.1	0.5	2 mN.m
Self-braking torque (N.m.)	0.11	0.55	6	0.1	0.4	2 mN.m
Max speed (rev/min)	60	30	140	>40	30	100 (Cont) 1 (Step)**
Min angular step (arcsec)	1	0.5	1	1	0.5	10
Dynamic range (kHz)	2	2	2	4	4	4
Supply voltage (V)	12	12	12	12	12	12 (or lower)
Operating current (mA)	<300	<400	15,000	300-400	<400	<100
Motor weight (g)	220	360	800	30	50	10
Dimensions (mm x mm)	∅38x99 with encoder	∅50x100 with encoder	∅80x80	∅30x23	∅50x30	∅8x13 ∅10x15

Table 3. Summary technical specifications for Piezo Rhino™ & Piezo Beetle™

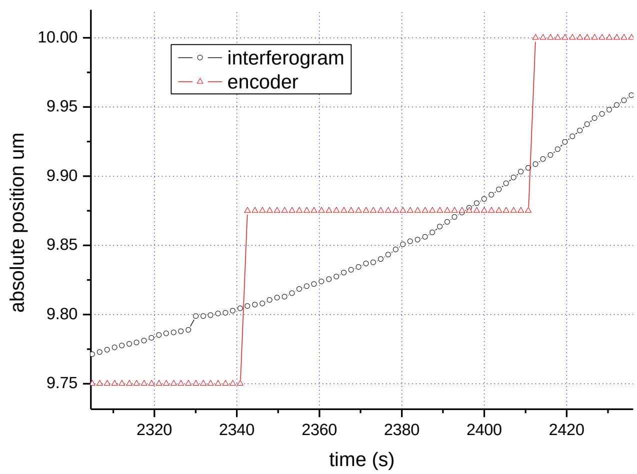
***Specifications will vary depending on requirements**
****Cont = Continuous mode; Step = Stepping mode**

Use of the new Piezomotor technology within commercialized products

A range of products utilizing the new piezomotor have been designed and successfully commercialized for use within biomedical research, micro/nanoelectronics, photonics and nanotechnology. These products include computer-controlled, state-of-the-art nanopositioning stages with extended travel range (e.g. 10-100 mm), XYZ-based nanomanipulators, high precision rotary/angular stages and miniature hybrid/robotic systems.

Examples of commercialized products using the new piezomotor. Left to right; Model PRS-1 (Precision Rotary Stage), NTS10 (linear nanopositioning stage), NM3D-25VP (Nanomanipulator).

The following graph illustrates experimental measurements obtained using a linear nanopositioning stage designed around the new piezomotor. In this example the minimum step size (3 nm) and velocity (15 nm/s) of the nanopositioning stage was verified by laser interferometer.



Movement of linear nanopositioning stage (Model NTS10-125) - steps indicate readings of the encoder, every 125 nm. (from "*IEEE Circuits & Devices Magazine, Dec 2006*")

Application Examples

The unique properties of the new piezomotor will provide important advantages with broad applications in many fields within science, engineering, medicine and manufacturing. It is not possible within the context of this paper to consider all such applications. In this paper we will discuss just one application within the field of defense & security, where it is believed the new technology will provide significant benefits.

Defense & Security Applications for the new Piezomotor

In long-range pointing applications, very small deviations in angular position may convert to substantial target tracking error. In defense applications this concerns all currently used rotary positioning devices in Infra-Red Search and Track (IRST) systems, as part of Light Detection And Ranging systems - LADAR (or alternatively LIDAR); in visible and IR target identification elements of Laser Perimeter Awareness Systems (LPAS); in Airborne Laser Weapon Systems (ABLWS); and generally with the broad family of electro-optic/infrared/laser radar/millimeter wave (EO/IR/LADAR/MMW) sensors used within Battle Management, Command, Control, Communications, Computers, and Intelligence (BMC4I) systems.

Requirements for these rotary systems are very stringent. Much attention has historically been given to the enhancing of the signal processing aspects of these systems and not so much to the enhancement of the mechanics of the drives (scanning subsystems). Indeed, most existing systems have inherited the scanning drive technologies from IRST and other infrared tracking systems that originated in the avionics technologies of the late 60's. These, however, have an inherited limitation deriving from their widespread application to infrared systems with low resolution and therefore a low demand on angular accuracy and dynamic response. For the future requirements of long-range tracking systems involving modern high-resolution cameras and narrow beam laser tracking and scanning, much higher demands on angular accuracy and dynamic response are called for.

Scanning systems such as those used for LIDAR have been used mostly for 3D imaging (geology), atmospheric physics, oceanography and other applications that do not require a real-time response (tracking). The use of LIDAR in military applications for target identification and 3-D imaging and autonomous navigation is relatively recent. Future LIDAR systems for long-range, fast, accurate tracking will now mandate novel drive systems extending the range of accuracy, repeatability and dynamic response beyond those needed by non-military applications.

The second important consideration in drive systems for advanced scan-tracking applications is the compensation for adverse environmental conditions such as platform vibrations, temperature and humidity changes, and inertial motion of the reference frame. To attenuate the detrimental effects introduced by the environmental conditions, most tracking systems are installed in sealed enclosures.

The photonics equipment mounted within them communicates with the outside environment through optical windows. To compensate for the movement of the platform of the vehicle the rotary stage is normally mounted with an Inertia Guidance System (INS) / Gyroscope, which provides feedback to the rotary stage on the movement of the platform. In response, the rotary stage compensates for this movement. Implicit in this is a requirement for the rotary stage to have a very fast response and a very high angular resolution. It will also need to have very low inertia to deal with overcompensation.

The new Piezomotor system could be used to address these critical performance limitations of conventional servomotor and stepper drive systems in defense and security applications. One such example is a proposed design of a novel 2-D gimbal system based on the new motor technology (see *Vision System Design*, June 2007, pp 43-46).

END **December 2008**

Commercial inquires

Discovery Technology International would be pleased to consider commercial inquires for custom (OEM) piezomotor systems. Our engineering team is capable of developing custom solutions for providing novel piezomotors with different sizes and parameters to meet many application requirements.

Discovery Technology International, LLLP
Sarasota, FL 34238
Tel: (941) 921 5111
Email. **Info@discovtech.com**
http://www.dti-piezotech.com