Novel Piezo Motor Enables Positive Displacement Microfluidic Pump

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ABSTRACT

We present the world's smallest linear motor and its use in tiny syringe and reciprocating piston pumps for microfluidic applications. SQUIGGLE® motors create direct displacement pumps that achieve nanoliter precision yet the pump assembly is the size of a pen cap. Linear motion directly moves a piston or bellows. The output pressure and flow are easily scaled by adjusting the piston diameter. SQUIGGLE motor pumps can miniaturize a variety of instruments including lab-on-a-chip systems, drug delivery devices, micro fuel cells, cooled computer chips, lubrication systems, spacecraft thrusters and liquid optics. A reference pump design is presented that achieves output pressure of 255 kPa, flow of 0.24 ml per minute at an oscillation frequency of 0.8 Hz and flow precision of 0.8 nl. In contrast, commercial oscillating membrane pumps are much larger, generate a 20 Hz or higher pulse frequency and produce much lower output pressure and accuracy.

Keywords: piezoelectric, motor, microfluidic, pump, syringe

1 INTRODUCTION

The SQUIGGLE® motor is the world's smallest linear motor, at only 1.55 X 1.55 mm square and 6 mm long *(figure 1)*. This actuator uses less than 0.1 Watt to produce 20 grams of force at 5 mm/sec. Its high linear force, power, precision and low cost make the SQUIGGLE motor ideal for numerous micro motion applications including mobile phone cameras, microfluidic devices, implantable drug pumps, deformable mirrors for adaptive optics, and basic laboratory research including MRI, vacuum and cryogenics.

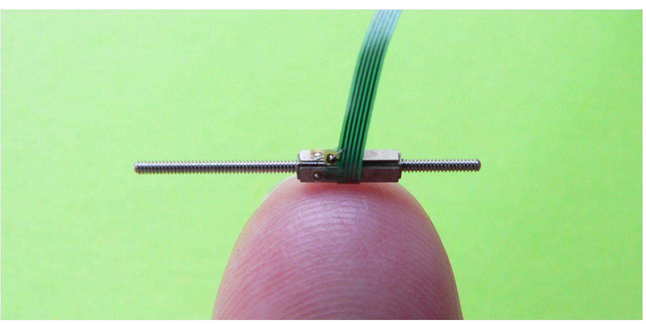

Figure 1: Linear SQUIGGLE motor measures only 1.55 x 1.55 x 6 mm

This novel motor can be used to create unique syringe and reciprocating piston pumps that are orders of magnitude smaller than existing micropumps, and also much more powerful and precise.

Most micropumps use flexing diaphragms and peristaltic motion to move fluids [1,2]. Examples include Van Lintel et al's micropump (1988) where the diaphragm is driven by the lateral strain of a bonded piezoelectric disk [3], and Smits' micropump (1990) which uses peristaltic motion from three piezoelectric actuators and etched silicon chambers [4]. A SQUIGGLE reciprocating piston pump overcomes several limitations of these diaphragm designs: it is dramatically smaller and provides quiet operation, no pressure pulses, much greater output pressure and flow, and robust priming and pumping of fluid filled with air bubbles and particles.

2 MOTOR OPERATION

The patented [5,6] piezoelectric linear SQUIGGLE motor uses ultrasonic standing wave vibrations in a threaded nut to directly rotate a screw *(figure 2)*. This unique operating principle "wraps" the vibration motion of the nut around the screw threads to directly produce linear movement without requiring additional mechanical conversion. The thread friction is not parasitic but is used to directly rotate the screw. The threads multiply linear force and position resolution and reduce linear speed. The result is a tiny high-force motor capable of sub-micrometer stepping and velocity control without the need for a position sensor and high speed servo control loop. Additional features include precise off-power hold and a manual adjustment option by turning the screw.

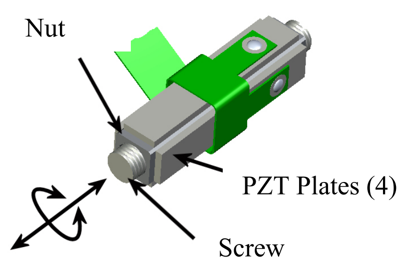

Figure 2: SQUIGGLE motor – a vibrating nut turns a screw

The nut vibration is sometimes described as a "hula hoop" or wobbling motion. A small axial preload maintains constant contact between the nut and screw threads, which causes the tangential friction force to rotate and translate the screw. Two orthogonal bending vibrations are combined to create the orbital motion. The two bending

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modes are created using orthogonal piezoelectric plates bonded to the outside of the metal nut.

The linear SQUIGGLE motor is a novel implementation of previous rotary motors using hula hoop vibrations. The first wobbling ultrasonic rotary motor was conceived more than 60 years ago (1948) by Williams and Brown [7]. It uses an orbiting stator to engage a round shaft or gear where tangential contact produces rotation. In 1995 a hula hoop rotary motor was demonstrated by Morita, using a thin-walled piezoelectric cylinder [8]. A miniaturized rotary motor, using two piezo plates and a hollow metal tube, was demonstrated by Koc, Catagay and Uchino in 2002 [9].

In the SQUIGGLE motor, four 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. The opposing d31 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 *(figure 3)*. 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 vibration mode is created by generating PZT strain in orthogonal plate pairs at the resonant frequency with 90 degree phase shift.

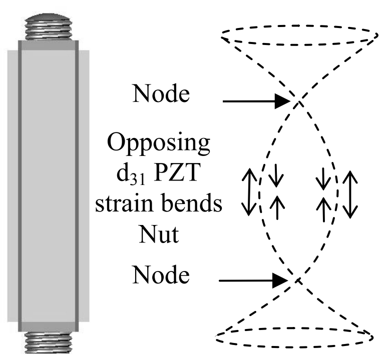

Figure 3: SQUIGGLE motor vibration mode shape (called "Hula Hoop" wobble or orbiting)

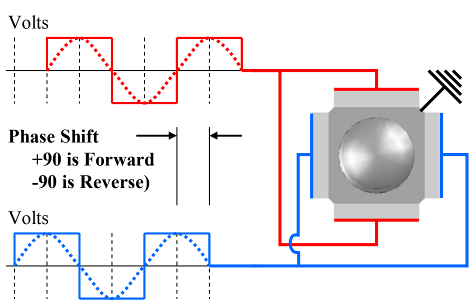

Figure 4: Two-phase motor drive signals (sinusoidal or square wave)

The PZT plates are activated using a two-phase electrical drive with a fixed frequency and +/- 90 degree phase shift *(figure 4)*. Drive frequency and amplitude depend on the motor model and vary from 40 to 200 KHz and 20 to 200 V respectively. Positive phase shift produces forward movement; negative phase shift produces reverse.

This motor design is scaleable to very small dimensions. Since its invention in 2003, the size and operating power have been reduced by an order of magnitude *(Table 1)*.

Motor Specifications	Dec 2003	Feb 2006
Diameter (mm)	8	1.55 x 1.55
Length (mm)	20	6
Screw Diameter (mm)	4.75	0.9
Stroke (mm)	50	10
Force (grams)	500	20
Speed (mm/sec)	2	5
Resolution (µm)	0.02	0.50
Frequency (kHz)	~ 40	~ 150
Voltage	100-200	20-40
Motor Power (Watts)	1	0.1

Table 1: miniaturization of SQUIGGLE motors

The smallest SQUIGGLE motors offer size, power and precision that can not be matched by conventional electromagnetic (EM) DC or stepper motors. EM motors have reached their practical limit of miniaturization. They become dramatically less efficient below 6 mm diameter and require operation at higher speeds. This higher rotation velocity requires even more gear reduction, which leads to even lower efficiency, reduced accuracy and increased size.

3 SQUIGGLE MOTOR SYRINGE PUMPS

SQUIGGLE syringe pumps have previously been demonstrated at a larger scale for research in magnetic resonance imaging (MRI) chambers *(Figure 5)*. A syringe pump delivers drugs to animals being imaged in a 1.5 Tesla magnetic field. This application highlights the non-magnetic properties of the piezo ceramic motor. 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.

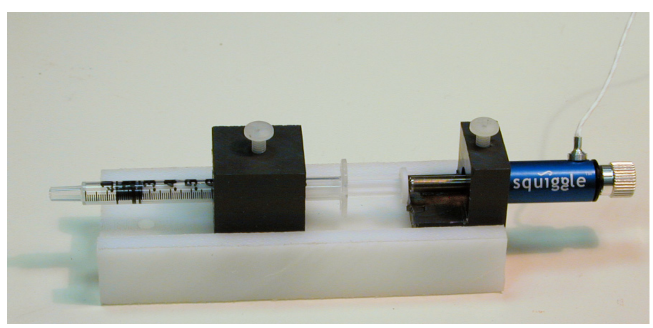

Figure 5: SQUIGGLE motor in an MRI-safe and image compatible syringe pump used for drug delivery. *(Courtesy of Dr. Richard Mazurchuk, Roswell Park Cancer Institute)*

Another SQUIGGLE syringe pump concept is shown in Figure 6. This wearable insulin pump, about the size of a mobile phone, integrates a 3 ml syringe and is moved by a 10 mm diameter SQUIGGLE motor. The motor produces 5 N of force and operates with closed-loop position feedback to ensure accurate doses, even with changing back pressure. For most patients, 3 ml of insulin lasts three days.

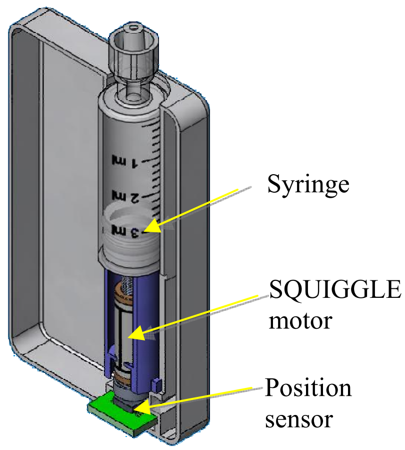

Figure 6: SQUIGGLE motor insulin pump concept

4 SQUIGGLE MOTOR MICROPUMP

The SQUIGGLE motor is a highly scaleable design and the newest and smallest versions can create very small fluid pumps. A reciprocating piston micropump design is shown schematically in Figure 7. This pump uses two linear motors and two pistons or syringes. It is also possible to replace the sliding pistons with flexible bellows.

This is a positive displacement pump where the speed and location of the pistons directly determines the flow rate and volume. The piston locations are measured using position sensors. Closed-loop control enables very precise motion control with 1 µm resolution.

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 ensures robust operation even with air bubbles or particles in the fluid. In addition, this pump has a strong self-priming ability.

The key scaling parameter of the pump is the piston diameter. For this example, a 1 mm diameter piston is used. This can be easily increased or decreased depending on the desired output pressure and flow.

This micropump is less than 28 x 6 x 3 mm or 450 cubic mm. By comparison, a commercial piezo diaphragm pump from Thin XXS Microtechnology is 4600 cubic mm [10].

Table 2 summarizes the key performance parameters of the SQUIGGLE motor micropump. Motor force, speed, stroke and resolution are shown with the corresponding fluid power parameters of pressure and flow.

Parameter	**Value**	**Units**
Motor Force	0.2	Newtons
Motor Stroke	6	millimeters
Motor Resolution	1	micrometer
Piston Diameter	1	millimeters
Pressure	255	kilo Pascals
Peak Flow	0.24	milliliter/minute
Frequency	0.83	Hertz
Flow Resolution	0.8	nanoliters
Pump Size	450	cubic millimeters
Peak Power	0.2	Watt

Table 2: Performance of SQUIGGLE motor micropump

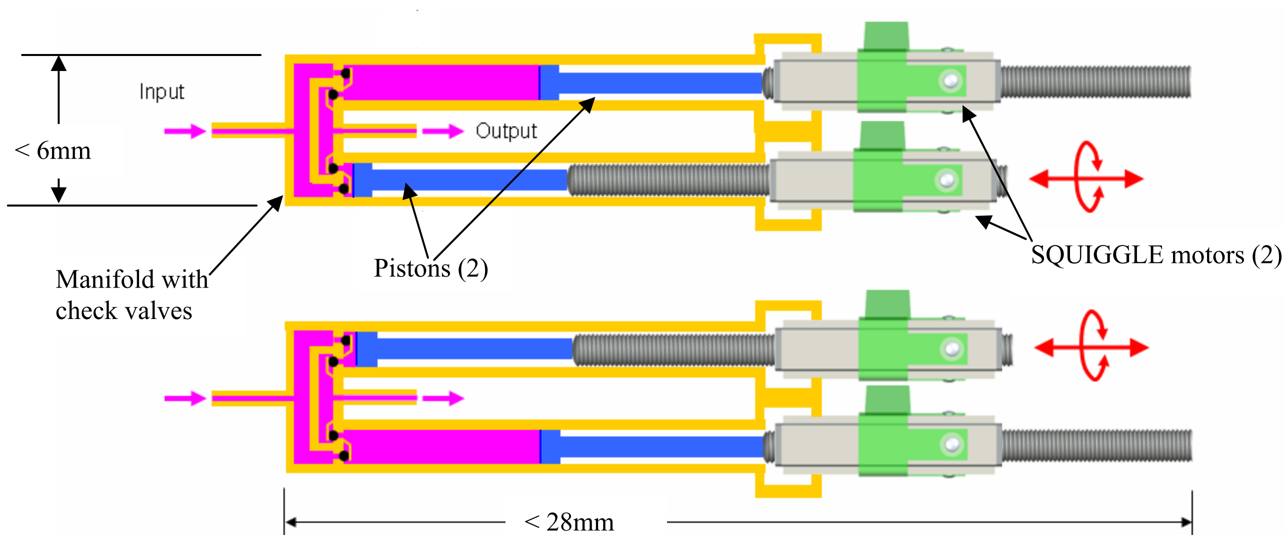

Figure 7: SQUIGGLE motor reciprocating piston pump (two views of pump cycle are shown).

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Another unique attribute of the SQUIGGLE motor pump is its wide dynamic range. While high pressure and flow are available, the pump can also 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.

5 OTHER MICROFLUIDIC APPLICATIONS OF SQUIGGLE MOTORS

SQUIGGLE motors have other potential uses in microfluidic applications. One example is using arrays of motors to form an active "bed of nails." A fluid chip can rest on this array and each motor can be moved individually to open and close valves or switch fluid flows.

Other examples are implantable drug pumps, biopsy tools, fluid collection, "smart pills," optical scanning, and adjustable valves/shunts where precision movement, dosage control and long battery life are essential.

SQUIGGLE® motor is a registered trademark of New Scale Technologies, Inc.

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