This paper exemplifies the capabilities of the Piezo LEGS® motor in combination with the DMC-30019 Galil controller in a closed loop system. As a system, motor and controller are capable of positioning on a nanometer level and perform advanced contouring with little deviation from the target. Piezo LEGS® technology is characterized by its high resolution in movement, high pushing and holding force, and its friction coupled movement free from backlash and mechanical play. The dynamic speed range is nanometers per second up to millimeters per second. The technology is an excellent fit for a wide range of high precision applications in markets such as medical devices, optics, photonics and semiconductor equipment.

1. INTRODUCTION
Piezo LEGS® is a motor technology for linear and rotary motion. The principle of these walking type piezoelectric motors is a number of actuators working together to take steps and move a ceramic bar or disc (Figure 1). The bimorph actuators stretch and bend from side to side when applying the appropriate drive signal. Step rate is determined by the signal frequency, but with step length being force and temperature dependent, speed will not be constant in open loop operation. Friction coupling between the tip of the actuator legs and the drive bar/disc ensures high pushing and holding force, and movement without mechanical play or backlash. These motors are never driven in resonance; the movement is always quasi-static and controlled.

With controlled sequencing of the electrical drive signal and with high resolution digital to analog conversion of signal voltages, the Piezo LEGS® has the capability of very fine positioning and exact motion profiling. As an example, the linear Piezo LEGS® motors are capable of sub-nanometer positioning and movement in a dynamic speed range from nanometers per second up to several millimeters per second. The push and hold force of a linear motor ranges from a few Newtons up to hundreds of Newtons (depending on model). Rotary motors have piezo actuators placed in a circle and can deliver direct drive at high torque.
The DMC-30019 is a motion controller with an internal Piezo LEGS® amplifier board from company PiezoMotor. Control architecture and hardware comes from Galil Motion Control, Inc. – an interface familiar to engineers worldwide. Setting up a system with the DMC-30019 controller and Piezo LEGS® motor is not much different from a conventional Galil system with a DC servo motor.

2. TEST SETUP
The test setup for demonstrating the operation of Piezo LEGS® and the DMC-30019 controller consists of a high quality linear slide with side-mounted motor of model LS15. On the opposite side of the slide a high resolution Mercury II 6000 optical encoder and glass scale (from MicroE Systems) are mounted. Motor and encoder are connected to the DMC-30019.

The encoder interpolation level can be selected to give maximum resolution of 1.2 nm. Noise level is about ±6 nanometers. In a perfectly stable environment the encoder readout will still be ±6 nm. Figure 2 below show encoder position data when the motor is disconnected from the controller.

3. EXPERIMENTS
3.1 Point-to-Point Positioning
The first experiment is done with a 1.2 nm resolution setting on the encoder. We want to demonstrate point-to-point positioning using these specific controller settings:

- TM125; ‘Update Time
- KP1.5; ‘Proportional Constant
- FV1.5; ‘Velocity Feedforward
- KI0; ‘Integral Constant
- KD0; ‘Derivative Constant
- SP9999984; ‘Speed
- AC999948288; ‘Acceleration
- DC999948288; ‘Deceleration

Commands sent were:

- SH; ‘Servo Here
- DP0; ‘Define Position
- PA10000; ‘Position Absolute
- BG; ‘Begin

The resulting controlled movement is 12 μm (10,000 encoder counts) with completion in less than 20 ms – see Figure 3 below. When settled, the position is held within ±6 nm, which is also the noise level of the encoder.

The second run is using higher settings for the velocity feedforward coefficient. Velocity feed-forward generates an output bias signal in proportion to the sample to sample change in reference position (i.e. the wanted speed). With increased value the motor will follow the commanded position better.
This is the value used for velocity feedforward (other settings are unchanged):

FV6; ‘Velocity Feedforward

The resulting controlled movement is 12 μm (10,000 encoder counts) with completion in about 10 ms – see Figure 4 below.

WT200; ‘Wait
PA40; ‘Position Absolute
BG; ‘Begin
AM; ‘After Move
WT200; ‘Wait
[…] ‘Continued sequence
PA120; ‘Position Absolute
BG; ‘Begin
AM; ‘After Move
WT2000; ‘Wait
JP #start; ‘Jump to Program Location

The program sequence generates a step ladder with steps of 24 nm (20 encoder counts). On every level the motor holds position ~200 ms. Data from the experiment is plotted in Figure 5a with detail in Figure 5b.

3.2 Step Ladder
The second experiment is for sequential stepping on a nano-scale. Again, the encoder resolution is set to 1.2 nm. These are the general controller settings:

TM125; ‘Update Time
KP1.5; ‘Proportional Constant
FV6; ‘Velocity Feedforward
KI0; ‘Integral Constant
KD0; ‘Derivative Constant
SP1024000; ‘Speed
AC10223616; ‘Acceleration
DC10223616; ‘Deceleration

This is the program sequence executed:

#start
DP0; ‘Define Position
WT200; ‘Wait
PA20; ‘Position Absolute
BG; ‘Begin
AM; ‘After Move

Figure 4. 12 μm move with small overshoot and fast time to settle. Black data points show actual movement whereas the green line is the reference position (commanded position).

Again the position settles nicely at 12μm ±6 nm. After, it holds the target position in closed loop.

Figure 5a. Step ladder with steps 24 nm each.

Figure 5b. Detail shows positioning at 96 nm. The position error is within the noise level of the encoder.
3.2 Constant Speed
The last experiment is running the motor at a constant speed. Speed was selected to 0.06 μm/s (50 counts/s). Controller settings are left unchanged. Commands sent were:

SH; ‘Servo Here
DP0; ‘Define Position
JG50; ‘Jog
BG; ‘Begin

The resulting speed plot is seen in Figure 6. Comparing with the commanded position of the controller, the error is less than ±6 nm. Slope speed is constant with position error no larger than the encoder position error logged with motor resting or completely disconnected (as shown in Figure 2).

The DMC-30019 can also handle more advanced contouring and PVT sequences (Position Velocity Time). The controller is programmable for 1,000 lines of code, and allows for concurrent execution of six programs. For questions or comments, please do not hesitate to contact PiezoMotor.

3. SUMMARY AND DISCUSSION
This paper exemplifies how well the DMC-30019 can control the Piezo LEGS® motor, both in point-to-point movement and when running at constant speed. The function of the system is very much dependent on the position feedback from the encoder. The step resolution of the motor is in fact sub-nanometer, meaning it would be possible to improve the positioning by selecting an encoder with more stable output (lower noise level). These experiments have been made with the purpose of showing what can be done in combination with an ordinary optical encoder.

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