Characterization of a Piezoworm Stage

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***Abstract*— A novel complementary clamp piezoworm stage was developed to be integrated into an XY configuration for applications such as microarray manufacture. The actuator is a complementary clamp piezoworm which acts directly on the stage slide without additional coupling. Open loop tests showed that the stage is capable of a no-load speed of 8.5 mm/s, a force capacity of 6 N and can move a mass in excess of 17 kg.**

I. INTRODUCTION

MANY active areas of research such as genomics, proteomics and MEMS manufacture [1]-[6] require an ultraprecision stage capable of nanometer accuracy while having a range of several millimeters. For example, genomics uses microarrays [7] to perform thousands of concurrent experiments on the same chip. A grid of microscopic drops is deposited on a chip. Drops of different solutions are superimposed on the initial drops depending on the type of test. The chip is typically a few centimeters in size and the spot density can be in excess of 5000 spot/cm^2 [7]. In this work, we intend to design a compact stage which is able to traverse a distance of 50 mm which will be later integrated into an XY stage.

The typical manner to address both large range and high accuracy is to mount a high accuracy actuator, such as a piezoelectric flexure stage, to a large range actuator, such as a linear motor [2],[4],[5]. However, this is bulky and complex to control. A different approach is to use a piezoworm (also called inchworm®) actuator which has two clamping piezostack actuators and an extender piezostack actuator mounted in a flexure frame. To traverse long distances, a sequence of clamp-extend-clamp steps is executed [6]. The piezoworm can also adjust its position within one step by keeping one clamp fixed and finely varying the extender piezostack to achieve nanometer accuracy.

Several variations of piezoworm-type actuators have been presented in the literature and most fall into two classes; 1) body of the piezoworm moving through a fixed guideway [6], and 2) rod moving through a fixed body of the piezoworm [8]. A slide or other guiding mechanism must be incorporated to function as an XY stage so that moments applied to the stage do not twist the actuator and cause it to bind. The interface of the slide to the actuator must be carefully designed so that there is no backlash and that the slide and actuator are in perfect alignment again so that binding will not occur. This paper presents a novel piezoworm stage design which acts directly on the slide to reduce the chance of binding and provides a zero-backlash interface. The design is based on the complementary clamp piezoworm developed previously in [9].

Section II describes the prototype piezoworm stage with the clamp designs. Section III then presents the experimental tests performed on the current prototype. Conclusions are summarized in Section IV.

II. STAGE DESIGN

The objective is to design a stage to have a range of at least 50 mm, maximize speed, stiffness and thrust while minimizing the mass and size. Mass is critical for constructing an XY stage because the second axis is mounted on top of the first at 90° so the lower axis must be able to move the payload plus the mass of the upper axis. Other design goals are to minimize wear and cost.

The piezoworm stage configuration and prototype are shown in Fig. 1. The piezoworm is mounted on a base plate and directly acts on a friction strip mounted on a crossed roller slide. An encoder is mounted on the other side of the slide which is used for position measurement and has a resolution of 10 nm. The extension flexures are used to ensure that the piezostack does not experience damaging shear or tensile loads. The flexure needs sufficient stiffness to ensure its resonant frequency is above the excitation frequency while not reducing the maximum extension significantly. The maximum operating frequency determined by the amplifier capabilities is 800 Hz.

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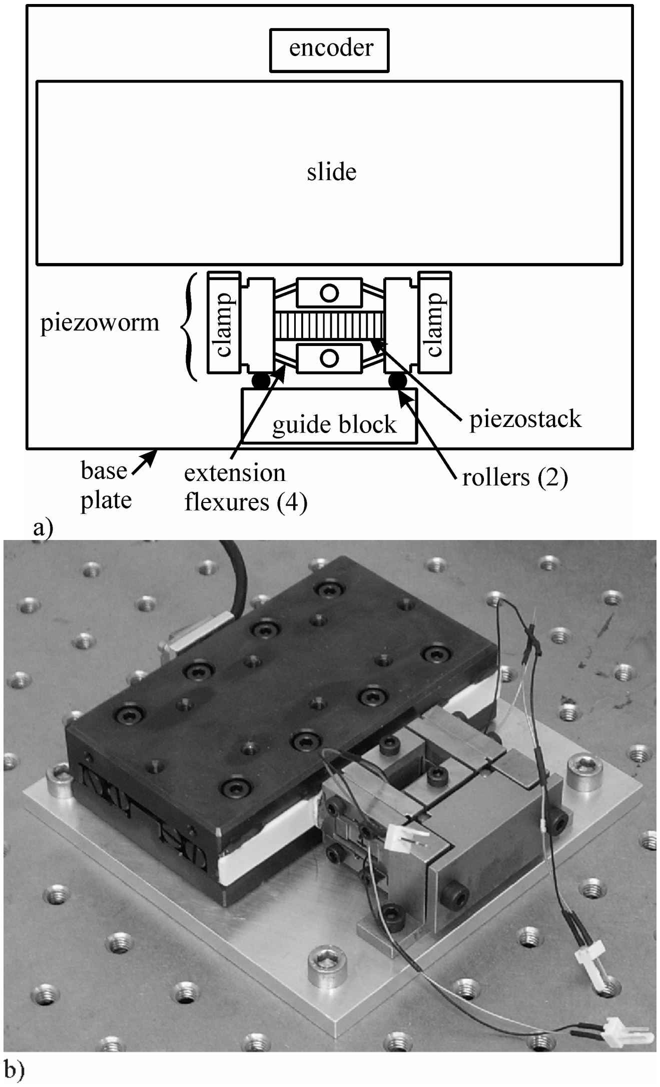

Fig. 1. Piezoworm stage a) general configuration, b) prototype.

To step to the right, the right clamp would be energized to grasp the slide and at the same time the left clamp would release it. Then the extender piezostack is energized which moves the slide to the right half the distance the piezo expands. The clamps switch such that the left clamp now secures the slide and when the extender piezo de-energizes the slide again moves right by half a step. By repeating this process, large range can be achieved [6].

Unlike most other designs, this piezoworm actuator pushes on only one side of the slide. This reduces the force transfer to the slide but permits a commercially available slide to be integrated into the design which reduces the cost. Binding is also prevented with this arrangement since the piezoworm can adjust for the deviations of the slide as it travels through its range. With the direct coupling, backlash is not an issue.

A guide block with rollers is mounted to the base plate on the non-clamping side of the piezoworm near the clamps to increase the force transfer to the slide. When a clamp begins to push on the stage the extension flexures may twist causing the clamp to push itself away from the slide. The guide block prevents the extension flexures from twisting, focusing the force of the clamp on the slide. The rollers ensure the guide does not interfere with the extension of the piezostack. Screws in the guide block allow for fine adjustment of the support to the structure. With both clamps disengaged, the screws are adjusted so that the slide can pass through its full range of motion without binding.

Ceramic strips are glued to the friction surfaces of the clamps and to the slide to reduce wear. Wear will increase the gap between the clamps and slide and degrade the performance of the piezoworm. The use of friction strips allows the clamp material to be optimized for stiffness and strength and not the wear properties. It also allows integration of a commercially available slide.

The piezoworm actuator is an improved version of the complementary clamp actuator developed in [9] and is shown in Fig. 2. A complementary clamp actuator is designed such that one voltage signal drives both clamps instead of a separate signal for each clamp as in traditional piezoworms. This reduces the number of amplifiers required for each axis from three to two which is a significant cost saving. To perform clamp switching using one signal, the clamps are designed to move in opposite directions as the clamp signal is varied. One clamp, referred to as normally unclamped (NU), grips when the voltage signal is at its maximum and the other clamp, called normally clamped (NC), grips when the voltage is zero. The clamp designs are shown in Fig. 3 and their design is described in the next section.

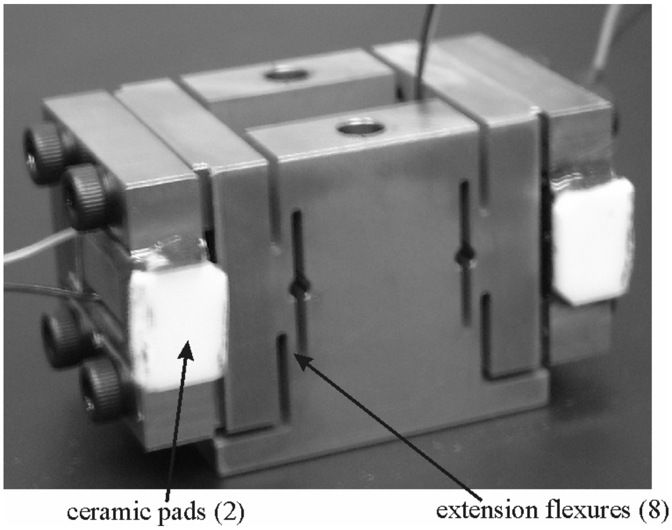

Fig 2. Piezoworm actuator from clamping side.

A. Clamp Design

The clamp configurations from [9] were redesigned to make them more compact and improve fabrication. Again, flexures are used to preload and protect the piezostacks. The clamps have almost identical flexure frames with only the bottom hole being different. The NC clamp has a tapped hole for a set screw, whereas the NU clamp has a through hole to permit adjustment of a set screw on the tab from the extension frame. The clamp flexure frame is bolted to the extension frame via four screws through the mounting holes.

The orientation of the tab that extends from the extension frame through the clamp frame determines whether the clamp acts as a NU or NC clamp. The NC clamp has the tab on the side closest to the clamping surface. The extension of the piezostack causes the clamping surface to move away from the slide eventually creating a gap when the piezostack is fully energized. The NU clamp has the tab oriented such that the expansion of the piezostack will cause the clamping surface to move toward the slide and maximum clamping force is achieved when the piezostack is fully energized. A set screw in each clamp is used to preload the piezostack. For the NU clamp, the tab on the extension fame is threaded for the set screw.

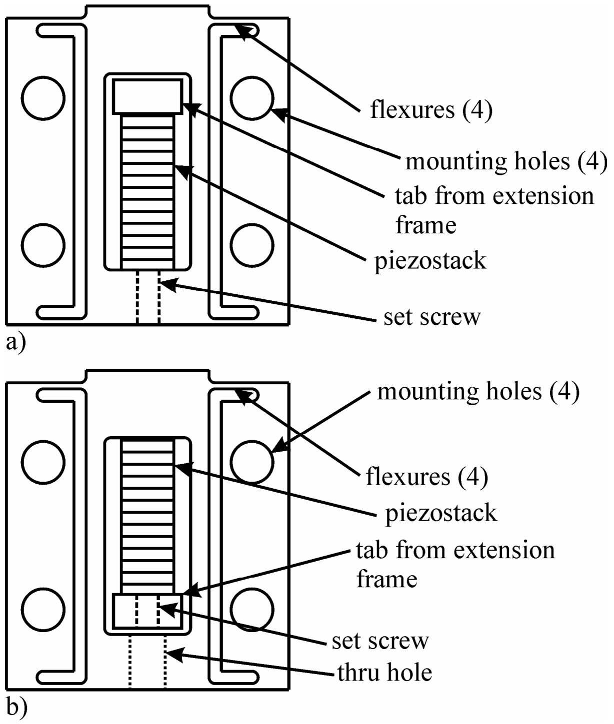

Fig.3 Piezoworm clamp configurations. a) NC clamp, b) NU clamp.

Using a common flexure frame configuration has several advantages. The mass of the NU clamp and NC are identical so that we can expect their dynamic behavior also to be identical. Also, several clamp frames can be fabricated simultaneously using wire electrical discharge machining (EDM). This will reduce cost and if a clamp is damaged, it could be exchanged for a new clamp instead of scrapping the entire piezoworm.

Both clamps use the same piezostack made of Navy Type II PZT (Sensor Technology BM500) having an area of 5 mm × 5 mm, a length of 11 mm, a free expansion of 12 µm and a stiffness of 60 N/µm. These piezostacks were chosen because they offer good free expansion and high stiffness in a small package size. The expansion dictates the stroke of the clamps and the larger the stroke the more accommodation for slide variation. A high piezostack stiffness will mean a higher clamping force.

The goal in the design of the clamp flexures is to minimize the flexure stiffness as much as possible so that the clamp would have the greatest range. The resonant frequency will be high because the mass of the moving part of the clamp is only about 6 grams. The flexure's length and width was determined by the available envelope and the thickness was set at 0.5 mm, the lowest value deemed practical for machining. Finite element analysis (FEA) performed using ANSYS [10] on the flexure frame showed the stiffness for the clamp to be 8 N/µm and the resonant frequency to be 5526 Hz. The resonant frequency is well above the maximum drive frequency of 800 Hz. The clamp range can be estimated from (1) [9] where k_p is the piezostack stiffness, k_f is the flexure stiffness, L_o is the free expansion and L_d is the constrained expansion. Using this relation the clamp range is estimated to be 10.6 µm.

$$L_d = \frac{k_p}{k_p + k_f} L_0 \tag{1}$$

B. *Extension Frame Design*

The displacement range of the extension frame is the step size of the motor. In order to maximize the speed of the motor, the expansion must be maximized while ensuring the resonant frequency is larger than the operating frequency. The extension flexure length and width were dictated by the envelope and thickness was selected to give a resonant frequency of about three times the driving frequency at 2803 Hz. The total effective stiffness of the flexures was 19 N/µm. A piezostack of the same material and area as the clamps was used but the design could accommodate a longer, 18 mm stack. It has a free expansion of 18 µm and a stiffness of 40 N/µm. Based on (1), the frame will have an expansion of 12 µm, and at a driving frequency of 800 Hz, the maximum speed of the motor is expected to be about 9.6 mm/s.

III. EXPERIMENTAL RESULTS

The prototype was subjected to several tests to assess its performance and the test setup is shown in Fig. 4. The piezoworm stage was mounted to a breadboard table with the NC clamp on the left side viewed from the perspective of Fig. 4. The encoder mounted to the slide (MicroE Systems Mercury 3500 with a resolution of 10 nm) was used to measure the position, x. A signal conditioning module provided with the encoder changes the encoder signal into a standard signal that can be read by Labview [11] running on a PC. The PC using a Real-Time operating system recorded the position and also supplied the control signals, u_C and u_{EXT}, to the amplifiers, DSM VF-500 [12]. The common clamp voltage, V_C, splits to provide the signal to each clamp, while the extender signal, V_{EXT}, controls the extender piezostack. A mass attached to the moving member via a cable around a pulley was used to apply a load to the piezoworm. The effects of operating frequency, applied force and payload mass on motor speed were investigated.

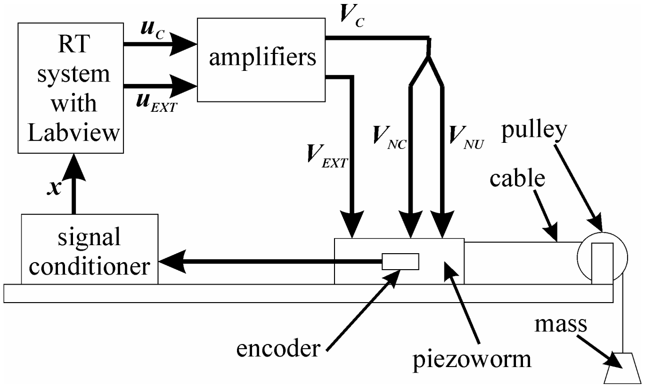

Fig. 4. Prototype Experimental Setup

The speed of the piezoworm is dependent on both step size and step frequency. The step size is a function of the piezoworm parameters, however, the step rate is limited by the amplifier bandwidth of 800 Hz. In this test, a trapezoidal waveform was used with the duration of the rising and falling portions of the waveform limited to 25% of the signal period. The common clamp signal is shifted by 90° relative to the extender signal so that the clamp signal has reached its extreme before the extender begins to move. Both signals range from 0 V to 200 V. The results are shown in Fig. 5. The maximum speed of the motor is 8.5 mm/s which is less than the predicted value of 9.6 mm/s most likely due to some slipping that is occurring. The predicted value assumed perfect friction surface contact between the clamp and the slide and no slippage. This speed is much faster than the 440 µm/s of our previous prototype [13] and faster than the commercial EXFO inchworm stage which has a top speed of 1.5 mm/s [14].

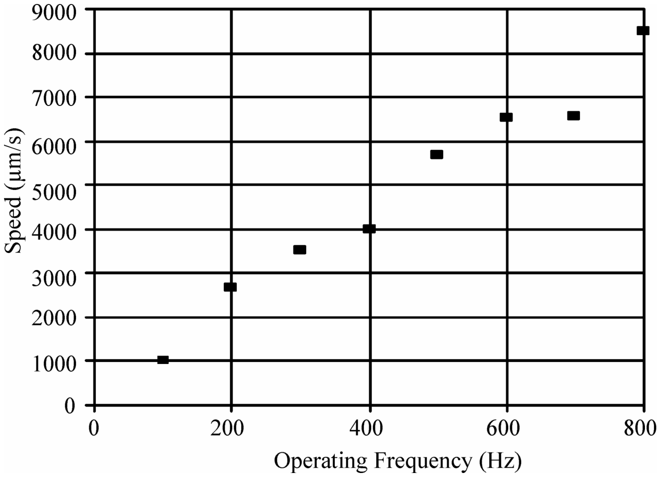

Fig 5. No-load speed versus operating frequency.

The effect of applied force was studied next using weights applied to the piezoworm stage using the cable and pulley. The same waveform as the previous test was used at an operating frequency of 500 Hz. The results in Fig. 6 show that the speed decreases roughly linearly with force to a maximum load of about 6 N. This was lower than the 12.5 N of our previous prototype [13], but should be expected since the number of clamp friction surfaces was reduced from four to two because the clamps act only on one side of the slide. However, the test was repeated, this time without the pulley but with the mass mounted on the slide. It was found that the piezoworm speed did not diminish as the mass was increased up to 17 kg. This result is promising since it is expected that the stage would be used for positioning a mass, including the other axis which would be mounted on top.

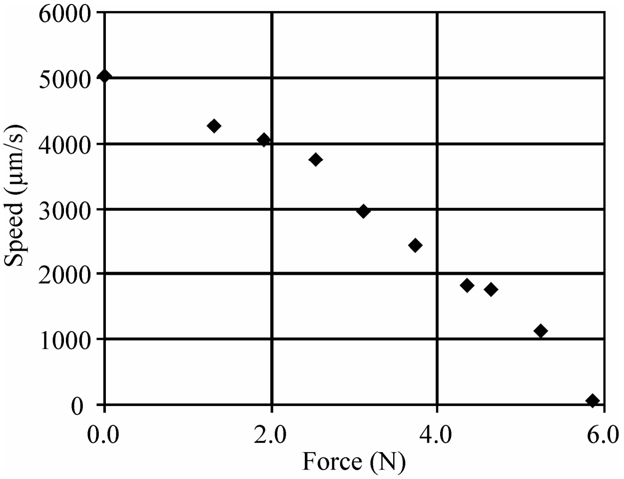

Fig. 6. Speed versus applied force.

IV. CONCLUSIONS

A novel piezoworm stage was developed which was designed specifically as a stage. It is an improvement on the complementary clamp piezoworm developed previously in terms of size, weight, manufacturability and performance. Tests show that the stage is capable of a no-load speed of 8.5 mm/s, a force capacity of 6 N and can move a mass in excess of 17 kg.

REFERENCES

[1] Y. Okazaki, "Precision Positioning Control Apparatus and Precision Positioning Control Method," US Patent 5 801 939, Sep. 1, 1998.

[2] W. Yao and M. Tomizuka, "Robust Controller Design for a Dual-Stage Positioning System," *Proc. of International Conference on Industrial Electronics, Control, and Instrumentation*, vol. 1, 1993, pp. 62-66.

[3] K. Tsai and J. Yen, "Servo System Design of a High-Resolution Piezo-Driven Fine Stage for Step-and Repeat Microlithography Systems," *Proc. of Annual Conference of Industrial Electronics Society*, vol. 1, 1999, pp. 11-16.

[4] S. Kwon, W. Chang and Y. Youm, "Robust and Time-Optimal Control Strategy for Coarse/Fine Dual-Stage Manipulators," *Proc. of IEEE International Conference on Robotics and Automation*, vol. 4, Apr. 2000, pp. 4051-4056.

[5] S. Kwon, W. Chang and Y. Youm, "On the Coarse/Fine Dual-Stage Manipulators with Robust Perturbation Compensator," *Proc. of IEEE International Conference on Robotics and Automation*, vol. 1, May 2001, pp. 121-126.

[6] B. Zhang and Z. Zhu, "Developing a Linear Piezomotor with Nanometer Resolution and High Stiffness," IEEE*/ASME Transactions on Mechatronics*, vol. 2, no. 1, Mar. 1997, pp. 22-29.

[7] M. Schena, "Microarray Analysis," John Wiley & Sons, New Jersey, 2003.

[8] D. Newton, E. Garcia and G. Horner, "A Linear piezoelectric Motor," *Smart Materials and Structures*, vol. 7, no. 3, 1998, pp. 295-304.

[9] S. Salisbury, D. F. Waechter, R. Ben Mrad, S. E. Prasad, R. G. Blacow, and B. Yan, "Design considerations for complementary inchworm actuators," *IEEE/ASME Transactions on Mechatronics*, vol 11, no. 3, June 2006, pp. 265-272.

[10] ANSYS, Version 9.0, Ansys Inc.

[11] LABVIEW Real-Time, Version 8.20, National Instruments Corp.

[12] Dynamic Structures and Materials LLC (2005, 01). "VF-500: Linear Piezo Amplifier" [Online]. Available: http://www.dynamic-structures.com.

[13] S. Salisbury, D. F. Waechter, R. Ben Mrad, S. E. Prasad, R. G. Blacow, and B. Yan, "Closed loop control of a complementary clamp piezoworm actuator," *IEEE/ASME Transactions on Mechatronics*, in press.

[14] EXFO. (2005, 05). "TSE-820: Translation stage with digital encoder" [Online]. Available: http://www.exfo.com.