Cansmart 2008

International Workshop

SMART MATERIALS AND STRUCTURES

23 - 24 October 2008, Montreal, Quebec, Canada

DEVELOPMENT AND ASSESSMENT OF A PIEZOWORM STAGE FOR USE IN AN XY CONFIGURATION

S. Salisbury[1], R. Ben Mrad[2], D. Waechter[3], E. Prasad[4]

[1]Department of Mechanical & Materials Engineering, University of Western Ontario, London, ON, Canada
[2]Department of Mechanical & Industrial Engineering, University of Toronto, Toronto, ON, Canada
[3]Nerac Inc., Tolland, CT, USA
[4]Sensor Technology Limited, Collingwood, ON, Canada

ABSTRACT

Many emerging applications including metrology, biomedical research and MEMS manufacture require an ultraprecision stage capable of nanometre accuracy and a range of several millimetres. A piezoworm uses two clamping piezostack actuators and an extender piezostack actuator to perform a sequence of steps to traverse large distances. It can also adjust its position within one step to achieve nanometre accuracy. A novel light and compact complementary clamp piezoworm stage was developed and integrated into an XY configuration. The complementary clamp configuration simplifies the driving requirements of the system. Tests showed good performance suitable for XY operation.

***Keywords**:* Complementary, piezoworm, precision, stage.

INTRODUCTION

Many active areas of research such as genomics, proteomics and MEMS/NEMS manufacture [1-7] require an ultraprecision stage capable of nanometre accuracy while having a range of several millimetres. 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 nanometre 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 and assembled so that there is no backlash and that the slide and actuator are in perfect alignment so that binding will not occur. In this work, a novel piezoworm stage is presented 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 concept developed previously in [9], however, it was redesigned to improve fabrication, integration into a stage and control. A prototype of the stage is tested to assess the performance.

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 actuator 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. Unlike most other designs [6, 10, 11], 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.

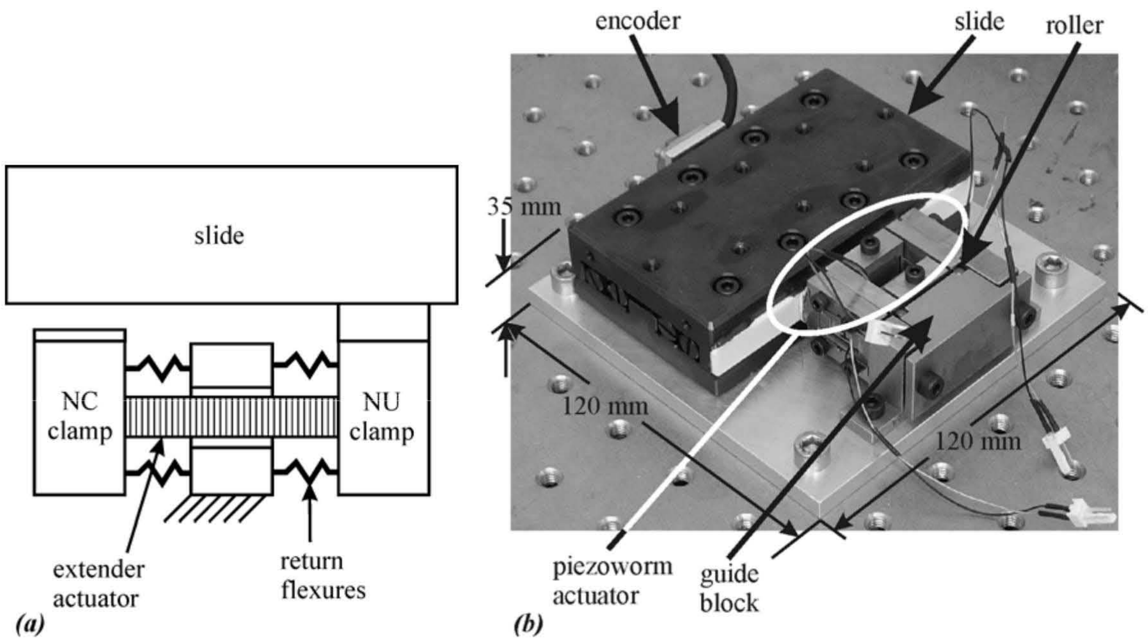

Fig. 1: Piezoworm stage a) general configuration, b) prototype.

The piezoworm actuator is an improved version of the complementary clamp actuator developed in [9]. 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 piezoworm design in [9] is not suitable for XY stage integration because of its size and clamp mounting arrangement. The NC clamp was fixed to the structure and all the motion was performed by the NU clamp. This was problematic during tracking because when the NC clamp was engaged the output could not be controlled and the control system had to wait until the NU clamp was re-engaged. This improved complementary clamp piezoworm has the clamps connected to a middle section via extension flexures. This allows both clamps to be mobile which permits control of the slide no matter which clamp is contacting the slide. The maximum operating frequency of the amplifier is 800 Hz.

The operation of the piezoworm stage is different from the design presented in [9] because it makes two half steps by each clamp rather than one full step by one clamp. 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 approximately half the distance the piezo expands (assuming the piezo expands equally in both directions). The clamps switch such that the left clamp now secures the slide and when the extender piezo de-energizes the slide moves again to the right by half a step. By repeating this process, large range can be achieved

Clamp Design

The clamp configurations from [9] were redesigned to make them more compact and improve fabrication and are shown in Fig. 2. 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.

Flexures are used to preload and protect the piezostacks. The clamps have almost identical flexure frames (Fig. 2) with only the bottom hole being different. 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 behaviour also to be identical. Additionally, several clamp frames can be fabricated simultaneously using wire electrical discharge machining (EDM).

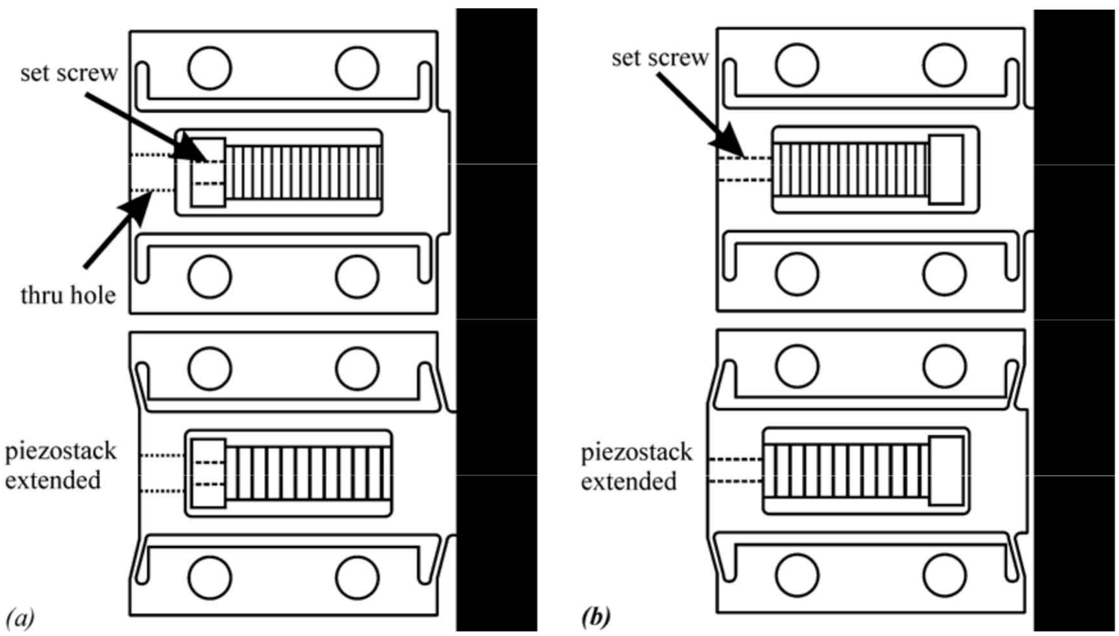

Fig. 2: a) NU clamp operation, b) NC clamp operation.

Extension Frame Design

The displacement range of the extension frame determines the step size and speed of the stage. For high accuracy positioning, the expansion must be maximized while ensuring the resonant frequency is larger than the operating frequency. This is important under closed loop conditions where resonance is undesirable. 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. The extension section of the piezoworm is constructed of the same stainless steel as the clamps and also has machined flexures. The extension flexure length and width were set at 3.5 mm and 8 mm respectively. An expansion of 12 μm at a driving frequency of 800 Hz gives the expected maximum speed of the motor to be about 9.6 mm/s. Prototype component tests led to a stiffness of 18.5 N/μm, resonance of 2540 Hz and an expansion of 13.2 μm.

EXPERIMENTAL RESULTS

The prototype was subjected to several tests to assess its performance. The effects of operating frequency, applied force and payload mass on motor speed were investigated.

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 each 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. 3a. The maximum speed of the motor is 8.5 mm/s which is much faster than the commercial EXFO inchworm stage which has a top speed of 1.5 mm/s [15].

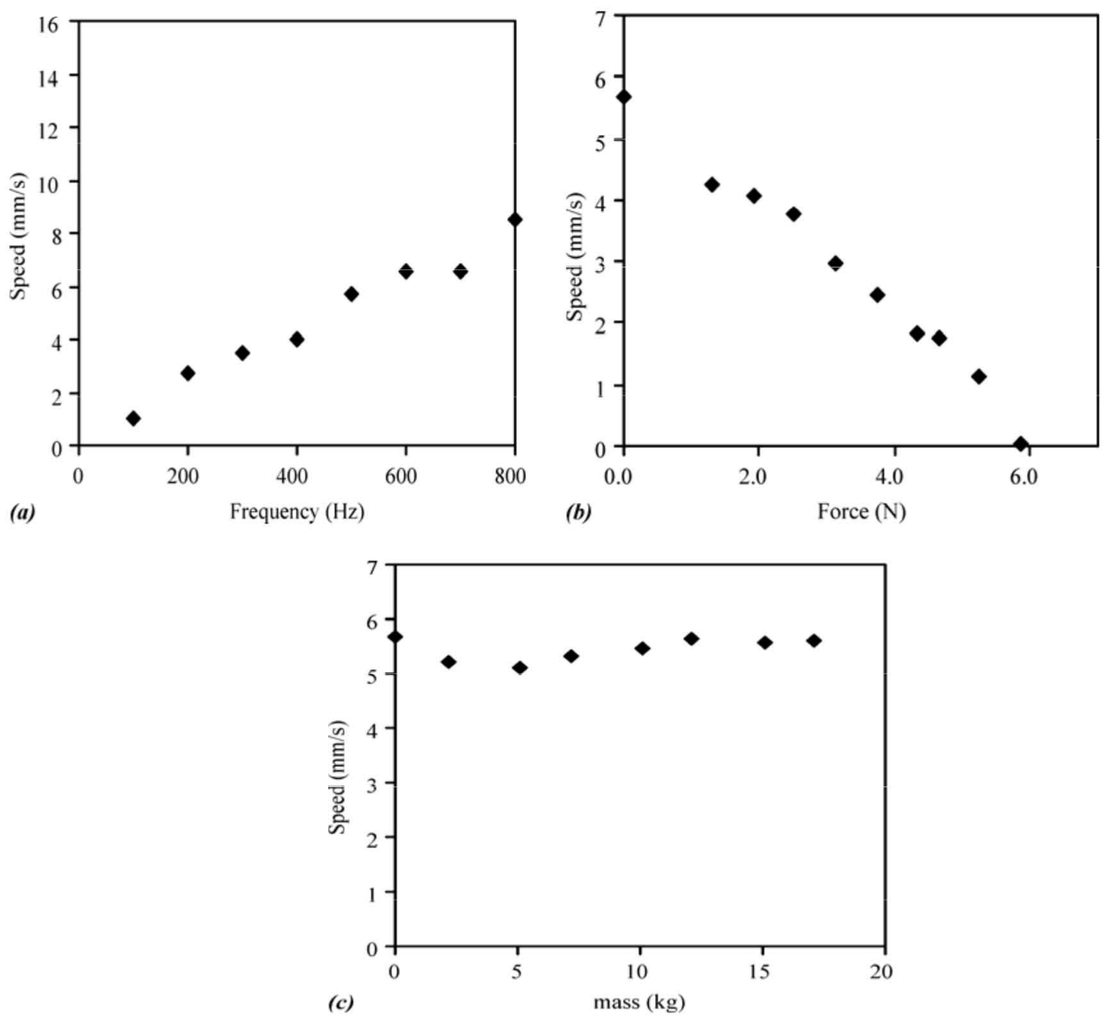

Fig. 3: (a)No-load speed versus operating frequency. (b)Speed versus applied force. (c)Speed versus mass.

The effect of applied force was studied next using weights applied to the piezoworm stage using a cable and pulley. The same waveform as the previous test was used at an operating frequency of 500 Hz. The results in Fig. 3b show that the speed decreases roughly linearly with force to a maximum load of about 6 N.

The final tests were conducted by mounting masses directly on the piezoworm slide. This mimics the intended application for the stage; to position a payload and also the other axis acting in the perpendicular direction. It was found that the piezoworm speed varied by less than 10% as the mass was increased up to 17 kg (Fig. 3c). This result demonstrates that the piezoworm stage has sufficient capacity to position the other axis plus a sizeable payload.

A second prototype stage was constructed and mounted to the first in a parallel-kinematics configuration using an adapter plate (Fig. 4). A closed loop controller was developed and the XY stage was able to successfully track the complex profile shown in Fig. 5.

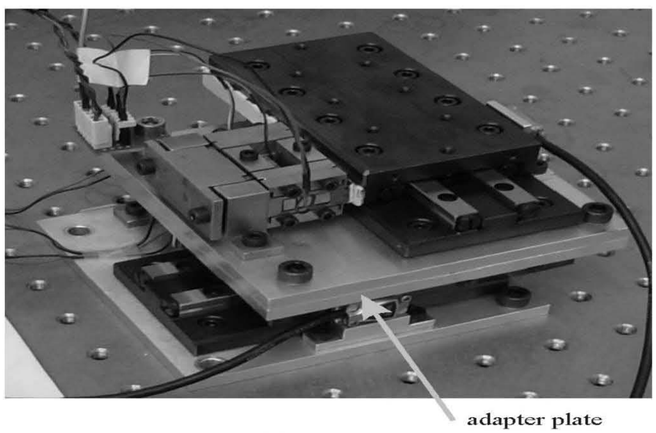

Fig. 4: XY stage prototype.

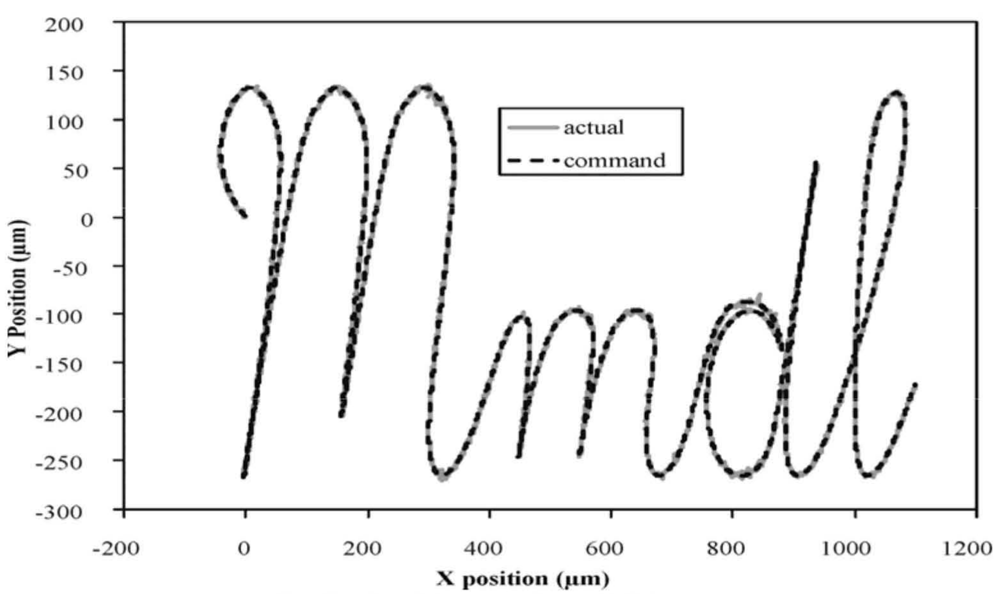

Fig. 5: Tracking profile of XY stage.

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 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.
10. W. May Jr., "Piezoelectric Electromechanical Translation Apparatus," US Patent 3 902 084, Aug. 26, 1975.
11. P. Tenzer and R. Ben Mrad, "A systematic procedure for the design of piezoelectric piezoworm precision positioners," IEEE/ASME Transactions on Mechatronics, vol. 9, no. 2, June 2004, pp. 427-435.
12. ANSYS, Version 12.0, Ansys Inc.
13. LABVIEW Real-Time, Version 8.20, National Instruments Corp.
14. "VF-500: Linear Piezo Amplifier", Dynamic Structures and Materials LLC, [Online document], [2005 January 10] Available at http://www.dynamic-structures.com.
15. "FAQ," Burleigh, [Online document], [2002 July 17] Available at http://www.burleigh.com