Computer Vision Assisted Measurement of the Displacements of a Bimorph Piezoelectric Cantilever Beam

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Abstract—**A computer vision assisted displacement measurement technique is proposed in this study. A sharp micro-marker is used as the marker of the bimorph piezoelectric actuator (PZT-5H). The micrometer actuation of the PZT-5H is monitored by a high resolution stereomicroscope. The micro-marker actuation is recorded as the driving voltage increases. Post image processing of the captures are conducted by MATLAB. The extracted vertex pixel values of the micro-marker from the captures are used to represent the PZT-5H actuation. The driving voltages are varied from 0 to 190 V which induce maximum displacements of 300 µm (1029 pixels). The proposed system can resolve a minimum displacement of 248 nm (1 pixel). Voltage to displacement linearity and repeatability are investigated. The PZT-5H chip has good linearity with driving voltages between 10 and 90 V. Future applications of this measurement technique are discussed.**

Keywords—displacement measurement; bimorph piezoelectric; cantilever; computer vision

I. Introduction

A cantilever beam is a rigid structure which has only one end anchored and another end is used to support the load. Cantilever structures can be found in both large construction (such as bridges, buildings and aircrafts) [1,2] and small microelectromechanical systems (MEMS) [3,4]. Techniques used to measure the cantilever displacements (deflection) depend on the target dimension. Computer vision based displacement measurement techniques have been used for large cantilever structures [5-8]. In these cases, the measurements are based on monitoring the displacements of the markers labelled on the structure by a digital camera. But for measuring the displacements of micro-structures, a higher resolution measurement technique is required.

Magnetic sensors can detect nanometer displacements [9,10]. The magnetic sensor usually consists of a magnetic component and a sensor. The magnet portion has to be fixed onto the target object when doing the measurements. Small cantilever structures such as the STEMINC bimorph piezoelectric chip (PZT-5H) are not capable of holding the magnet part. Measuring the displacements of small cantilever structures therefore require non-contact measurement techniques. Ultrasonic and optical detection techniques can do high resolution non-contact displacement measurements, but these approaches are expensive and hard to calibrate [11,12].

Recently, a computer vision based technique was used to measure small structure displacement [13]. The measurement resolution is degraded by the low resolution camera and the limited image processing techniques. Using these techniques it is impossible to get good resolution when using big markers and regular cameras. To measure micrometer displacements a high resolution camera and a sharp micro-marker are required.

A PZT-5H displacement measurement technique is proposed in this paper. By using a sharp micro structure as the marker, the PZT-5H displacements can be accurately represented by the number of pixels spanning the micro-marker. The voltage-to-displacement linearity and repeatability are reported. Potential applications of this technique are also discussed.

II. Materials and Methods

A. Measurement Tools and Materials

An image and drawing of the proposed displacement measurement system is seen in Fig. 1. The bimorph piezoelectric actuator (SM 311, PZT-5H) is purchased from Steiner & Martins, Inc., This device has a maximum actuation of 2 mm with a 200 Hz bandwidth. A regular laboratory power supply is used to trigger the high voltage module (EMCO F40, Schweiz, Switzerland). The EMCO F40 can provide DC voltages up to 2000 V. An adjustable resistor is used to modify the output voltages. A multimeter is used to monitor the voltage changes. A high resolution stereomicroscope (SM-1TSW2-L6W-10M, AmScope, CA, USA) (2748 × 3584 pixels) is used to track the micro-marker displacements. Microscopic captures are documented for every 2 V increase of the driving voltage applied to the PZT-5H chip.

B. Fabricating the Micro-Markers

A triangle shaped and Chromium prototyped structure (Fig. 2a) is fabricated using photolithography. Figure 2b shows the smallest black dot printed out by an HP Officejet Pro 8610 inkjet printer. The dot is invisible to the naked eye. Figures 2a and 2b are captured with the same microscopic magnification. The printed dot in Fig. 2b can be compared with the micro-marker shown in Fig. 2a. Compared to the micro-marker, the edges of the printed dot are rough. Clear and sharp edges are important for the vertex extraction in this study.

The use of photolithography can pattern a shape which is highly desired in this experiment. Since the fabricated edges of the triangle structure are clear and sharp, the vertices of the triangle structure are easy to detect. The displacement of PZT-5H can be better reflected by the number of pixels spanning the vertex (Fig. 3).

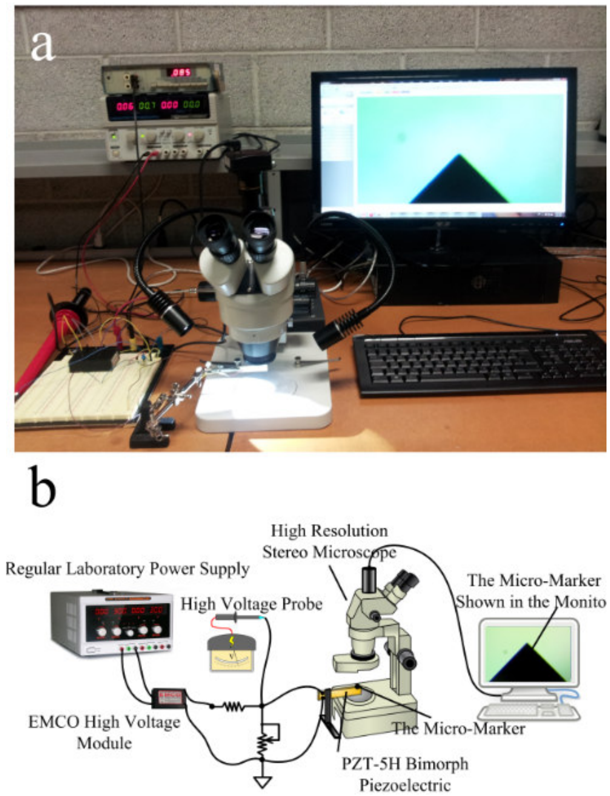

Figure 1 – (a) A photo of the PZT-5H displacement measurement system, and (b) the corresponding.

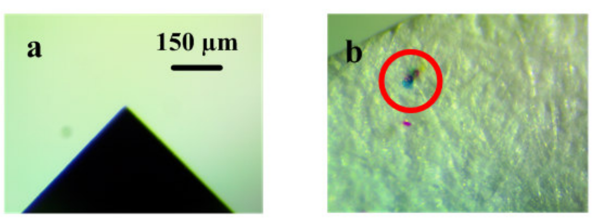

Figure 2 – (a) The fabricated micro-marker with ×10 magnification and (b) the smallest printable black dot (20 µm in diameter) printed by an inkjet printer on a regular paper (marked by a red circle. ×10 magnification). The mixed colors (RGB) of the printed black dot can be seen under microscope.

The micro-marker used in this study is fabricated in the cleanroom facility of Nevada Nanotechnology Center at University of Nevada, Las Vegas. The fabrication reagents includes Schott Boro Float glass substrate with Chrome coated (100 nm) microfluidic blank slides (with positive photoresist coated, Telic, Valencia, CA, USA), photoresist developer RD6 (Futurrex, INC., Franklin, NJ, USA), Chromium etchant (Sigma-Aldrich, Co., MO, USA) and photoresist remover (Microposit Remover 1165, Rohm and Haas Electronic Materials LLC, MA, USA). Open source integrated circuit (IC) layout tools Electric VLSI [12] is used to pattern the mask of the electrode array. GDSII output files from Electric VLSI were sent to Infinite Graphics INC. (MN, USA) for plotting (25,000 dpi resolution) on a plastic photolithography film.

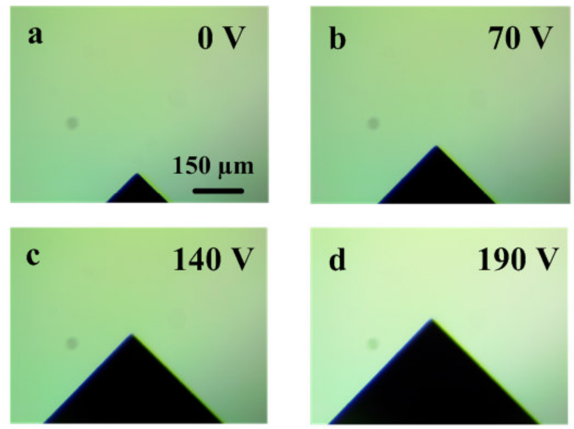

Figure 3 – The micro-marker spans over about 1029 pixels as the voltage applied to PZT-5H increased from 0 to 190V.

The substrates are covered by the patterned photomask and exposed to a UV light source for 45 seconds and then developed for 1 min in RD6. Substrates are then immersed in the Chromium etchant for about 15-20 seconds. Then the substrates are washed by DI water and dried out using nitrogen gas. The remaining photoresist is removed by Microposit Remover 1165. If the remover doesn't remove all of the photoresist Kimwipes (Uline, WI, USA) (wetted by Microposit Remover or DI water) can be used to remove the remaining photoresist.

The glass substrate micro-markers are cut into 1 cm by 1 cm pieces and attached to PZT-5H with double sided tape as depicted in Fig. 4.

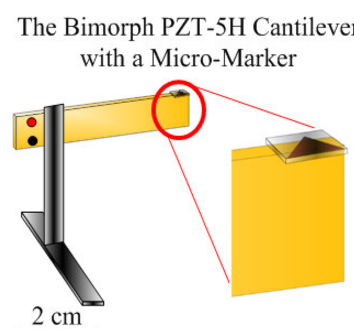

Figure 4 – The bimorph PZT-5H cantilever structure and the micro-marker.

C. *Image Processing*

The high resolution microscopic images are captured and saved. They are then converted to binary maps using MATLAB. The threshold for the MATKAB 'im2bw' function is 0.45. Due to the sharp edges of the micro-markers, the binary zoomed-in figures have clean edges as seen in Fig. 5. The zoomed-in binary maps are the vertices of the triangle shape. It is easy to locate the point (points) which has the largest Y axis values. The PZT-5H actuation is represented by the pixel value of the vertex of the triangle.

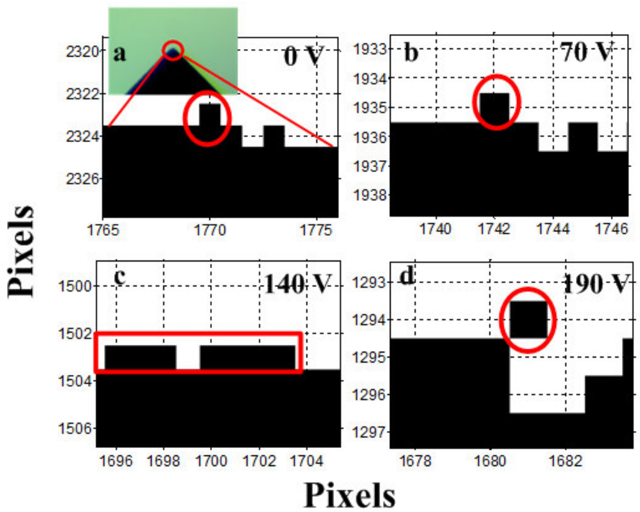

Figure 5 – The binary map of the vertex of the micro-marker. Each black square box is a pixel. The vertex pixels are marked with red circles in subfigures a, b and d. In subfigure c, there are 7 pixels (marked by a red box) have the same Y value.

As shown in Fig. 5, the vertex pixel value at 190 V is 1294 (Fig. 5d). The vertex pixel value at 0 V is 2323 (Fig. 5a). The real distance between the two pixel values is approximately 300 µm. So the apparent size of each pixel is (2323-1294)/300 µm = 248 nm.

III. Results

A. PZT-5H Voltage-to-Displacement Linearity

By adjusting the voltage divider seen in Fig. 1, displacements for every 2 V increase in the voltage applied to the piezoelectric cantilever can be recorded. The pixel deviations between every two neighboring input voltages are then plotted in Fig. 6. Within a certain range of input voltages, the micro-marker moves about 8-13 pixels for every 2 V increase in applied voltage potential.

Next, the linearity of the PZT-5H is investigated by subtracting the pixel value at 0 V from the pixel values at other input voltages. (The result is seen Fig. 7).

Figure 8 shows the probability of the pixel deviations for each 2 V increase. The driving voltages ranges from 0 to 190 V, so there are totally 190 V / 2 V = 95 samples. For each 2 V increase, the actuation of the PZT-5H chip is inconsistent (it's not linear). Figure 8 shows that in the 95 samples, the actuation of 10, 12 and 13 pixels have the biggest probability (near 15% for each). The dip at 11 is due to the small sample size (Fig. 8). More accurate sampling during 0 to 190 V can be achieved by using a digital to analog converter instead of using the voltage divider in this study (Fig. 1).

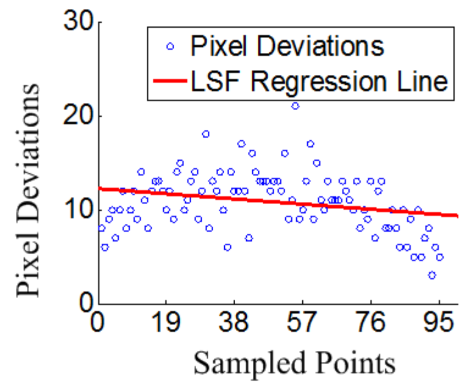

Figure 6 – Pixel deviations for every 2 V increase in the applied driving voltage.

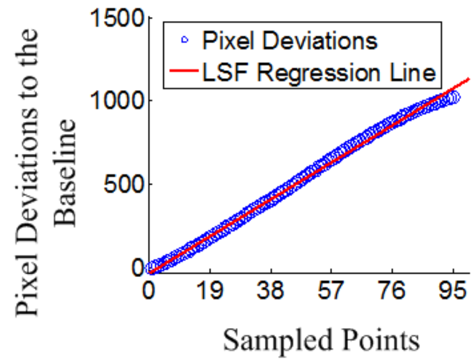

Figure 7 – Linearity of the pixel deviations at different input voltages.

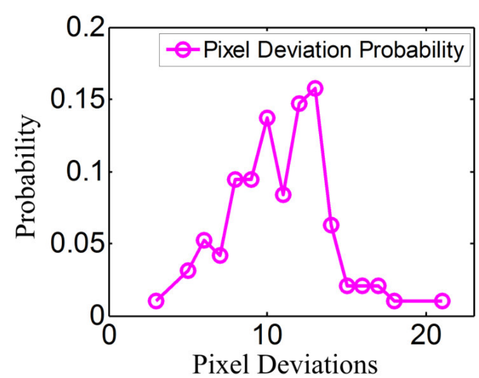

Figure 8 – The probability distributions of the pixel deviations for every 2 V increase.

The pixel deviations are directly calculated from the pixel values of the vertices in the binary map (Fig. 5). Several factors may affect the result including the vibrations of the experiment bench, subtle vibrations introduced by the manually voltage adjustment process and the light source variations in the environment. A variation of 8-13 pixels corresponds to roughly 2 to 3 µm which indicates the proposed technique has good resolution.

B. *PZT-5H Voltage-to-Displacement Repeatability*

The repeatability of the PZT-5H actuations were also investigated in this study. After the first voltage sweep was completed additional tests were conducted with time intervals of 1 min, 10 min, 20 min and 40 min. The test results are shown in Figs. 9 and 10. The sampled voltages are from 0 to 190 V in 10 V intervals. Experiment results show the repeatability is bad if there is almost no break between two experiments. The PZT-5H chip needs at least 20 min to recover the mechanical properties after the first test.

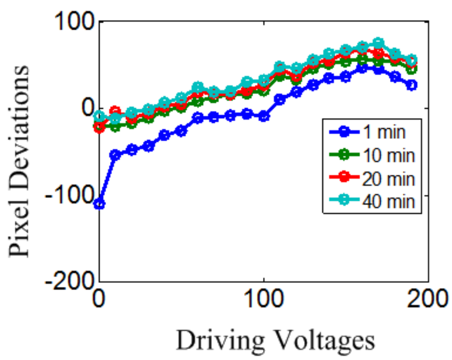

Figure 9 – The pixel deviations from the baseline.

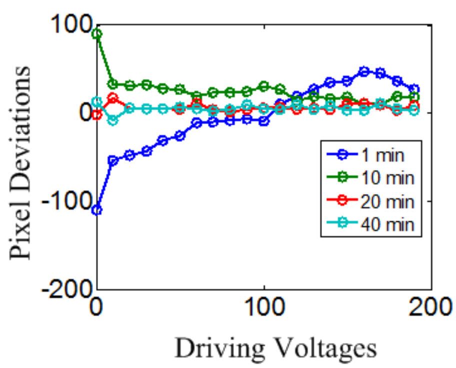

Figure 10 – The pixel deviations from two applied driving voltages with different time intervals.

The pixel deviations are relatively small if the PZT-5H driving voltages are between 10 and 90 V. The pixel deviations for each 2 V driving voltage increase become stable after 20 minutes following the previous experiments. The PZT-5H has the best linearity with driving voltages between 10 and 90 V. At low and high driving voltages, the linearity and the repeatability are poor even with a break time between experiments longer than 40 min.

IV. Conclusion

A bimorph piezoelectric cantilever displacement measurement technique is proposed and developed in this study. Sharp micro-markers are fabricated using photolithography. High resolution stereoscope imaging is used to monitor the micro displacement of the micro-marker. Clear edges are obtained by using the high resolution stereomicroscope. The vertices of the triangle-shaped micro-marker are tracked to measure the displacement of the PZT-5H chip. Experiments show that the PZT-5H chip works in good linearity from 10 V to 90 V.

All actuators that can fit into the microscope slot with micrometer actuations can be measured by this technique. The displacement data of the PZT-5H acquired from this study provides important references as the PZT-5H is used to hold the top plate of the digital microfluidic systems [13-15] in our future study.

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