Two-dimensional Laser Scanner with Low Mechanical Cross Coupling based on Piezoelectric Actuators

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Abstract: Traditional two-dimensional laser scanners usually employ two-degree-of-freedom flexible hinges. However, these flexible hinges suffer from mechanical cross coupling between axes, which will reduce the scanning accuracy and stability. To overcome the above disadvantages, a compact novel laser scanner based on piezoelectric actuators is presented. The scanner uses only three one-dimensional flexible hinges to achieve two-axis feature. The mechanical structure and principle are detailed. Then the capabilities of the scanner are tested by a performance test system. The test results show that the scanner has a tilt angle of 43.19 mrad for X-axis with resonance frequency at 149.21 Hz and 2.41 mrad for Y-axis with resonance frequency at 232.59 Hz. Its scanning nonlinearity is reduced from 3% to 0.5% for X-axis and from 6% to 1% after compensation. The test results and the actual scanning images prove the low mechanical cross coupling.

1 INTRODUCTION

Due to high precision, fast response, large force output and low power-consumption, amplified piezoelectric actuators (APAs) are widely applied in biological engineering, nanofabrication, and robotics and so on (Bouchilloux et al., 2004, Domke et al., 2011, Park et al., 2012, Yang et al., 2010). Especially for laser scanners which can precisely control the directions of laser beams, APAs are one of the main driving methods (Sweeney et al., 2002). In addition to APAs, flexible hinges are also the key structure for laser scanner. They can withstands stress and offers deformation when the scanner works.

Generally, to achieve two-dimensional (2-D) adjustments of laser beams, two-degree-of-freedom (2-DoF) flexible hinges have to be used. Unfortunately, almost all 2-DoF flexible hinges suffer from mechanical cross coupling between axes. In other words, motion of one axis can be affected by the other one, which will significantly reduce the accuracy and stability of laser scanner (Chen et al., 2015b, Jing et al., 2015, Shao et al., 2018). Some scanners employ two 1-D laser scanners to obtain 2-D features (Chen et al., 2015a). However, these designs increase system complexity and volume. There are two methods to deal with cross coupling effect. One is to use decoupling control algorithm, which is generally difficult to design and implement. The other one is to reduce the mechanical coupling ratio. Therefore, a novel structure with small or even zero interference between axes is strongly demanded.

In this paper, a new two-dimensional laser scanner based on three APAs is proposed. Through special mechanical design, the scanner employs only three 1-DoF flexible hinges to achieve two-dimensional laser deflection, which can effectively reduce the cross coupling. The structure and principle of the scanner are detailed. To investigate its performance, a test system is built up based on position sensitive detector (PSD). The test results show that the scanner has different resonant frequency in the two axes. The scanning images also prove the low mechanical cross coupling.

2 STRUCTURE AND PRINCIPLE

Flexible hinges are widely used in precision positioning. Various geometries of flexible hinges have been reported and studied (Wu et al., 2018).

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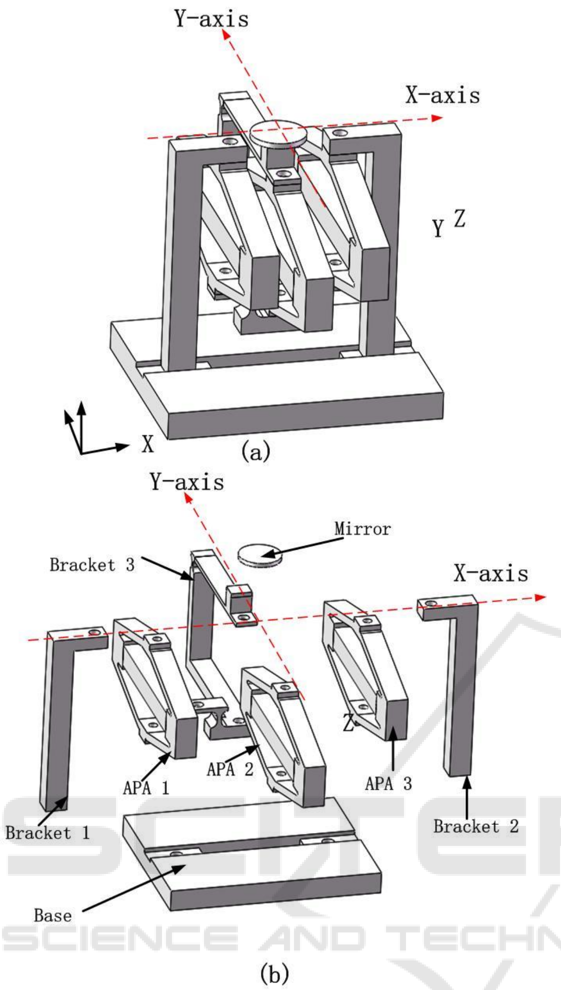

Figure 1: Structure of the scanner, (a) isometric view and (b) exploded view.

However, mechanical cross coupling of multi-axis flexible hinges is inevitable. Therefore, 2-D laser scanner employs flexible hinges suffers from inter-axis interference.

To overcome the above disadvantages, a novel structure of laser scanner based on APAs is introduced, as shown in Fig. 1. Figure 1(a) is the isometric view of the scanner and Fig. 1(b) shows the exploded view. The scanner consists of base, three supports, three APAs and mirror.

Brackets 1 and 2 have same L-shaped features. Their bottoms are fixed on the base. Two APAs (P06.X100A, Harbin Core Tomorrow, China) are fixed with the top edges of the two brackets, of which their bottoms are connected to brackets 3. Bracket 3 has a complex heterosexual structure, as shown in Fig 2(c). APA 3 and mirror are fixed with it.

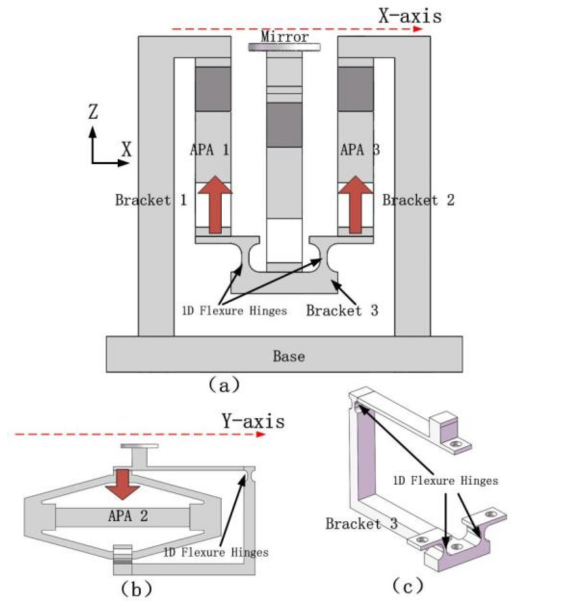

Figure 2: Principle of the X-axis deflection (a) and Y-axis deflection (b) and the structure of bracket 3 (c).

Figure 2 shows the working principle of the proposed scanner. As shown in Fig 2(a), when different voltages are applied to APAs 1 and 2, they will have different displacement in the Z-direction.

Then the bracket 3 will tilt with APA 3 and mirror in the X-axis. If a voltage is applied to APA 3, it will have a –z direction displacement and the mirror will tilt in the Y-axis (Fig. 2(b)). If applying three different voltages to the APAs, the mirror will tilt in X-axis and Y- axis simultaneously. Note that there are only three 1-d flexible hinges on the bracket 3 and they are working in different directions. These hinges have no mechanical cross coupling, as same as the scanner.

After design, the scanner has been manufactured and assembled.

3 PERFORMCE TEST

3.1 Performance Test System Design

To study the performance of the scanner, a test system was built up, as shown in Fig. 3. It consists of a He-Ne laser, a PSD (DRX-2DPSD-0A01-X, Daruixin, China), a drive circuit and power supply, a data acquisition card(USB 6361, National Instrument (NI), USA), and a software system (in PC).The software system was designed based on NI's LABVIEW software. Different control signals were generated by the software, output by the data

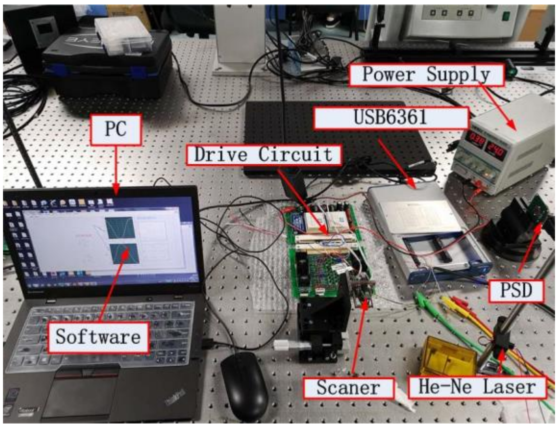

Figure 3: Performance test sytem.

acquisition card and amplified by the drive circuit. The circuit can provide maximum voltage of 150volts and power of 30 watts, which enough drive the scanner to work. Then, the PSD can real-time detect and output the position information of laser spot reflected by the scanner, which is collected by the same data acquisition card. At last, the software can figure out the performance of scanner, such as deflection angle, open-loop frequency response, hysteresis effects and nonlinearity.

3.2 Performance Test

Voltages from 0 volt to 150 volts are applied to the scanner and the relationship between the deflection angle and drive voltage is shown in Fig. 4. The maximum angle of the scanner is 43.19 mrad for X-axis and 2.41 mrad for Y-axis. It is clear that the

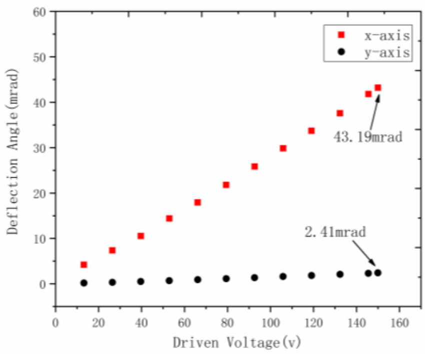

Figure 4: Relationship between the deflection angle and drive voltage.

scanning angles of both axes are linear to the drive voltages. The great difference in angles of different axes may be attributed to the different mechanical structures. The tilt mechanism of Y-axis needs to be optimized and improved.

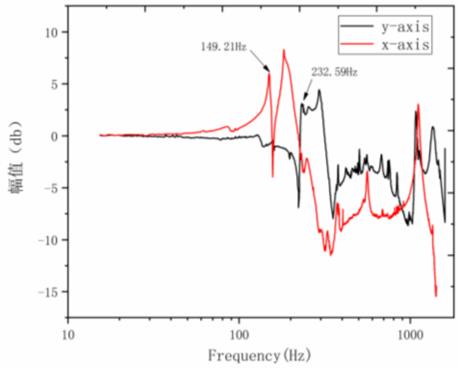

Figure 5: Frequency response of the scanner.

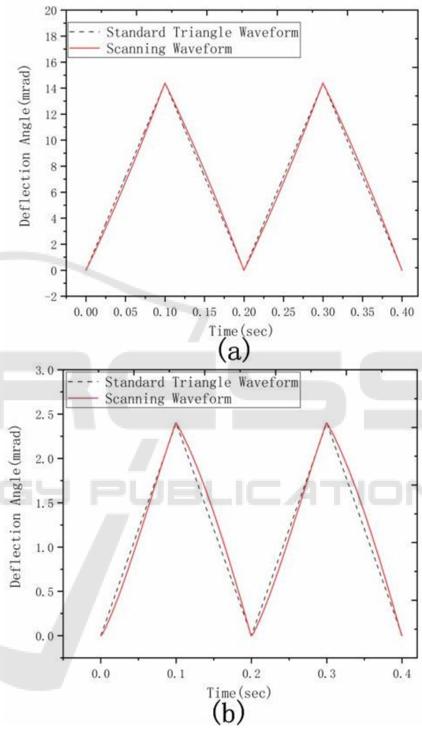

Figure 6: Scanning waveforms of the scanner with a drive voltage of a 5-Hz triangle wave for X-axis (a) and Y-axis (b).

Sine waveforms of different frequencies are used to the scanner to study the dynamic response of the scanner, as shown in Fig. 5. The first resonant frequency of X-axis is 149.21 Hz and 232.59 Hz for Y-axis.

Triangle waves of different frequencies are applied to the scanner to study its relative performance, as shown in Fig. 6. It can be found that the rising line and falling line of the waveform deviate from standard triangle waveform, which is caused by the hysteresis effect of the PZT stack in the APA. The amplitude of the drive triangular

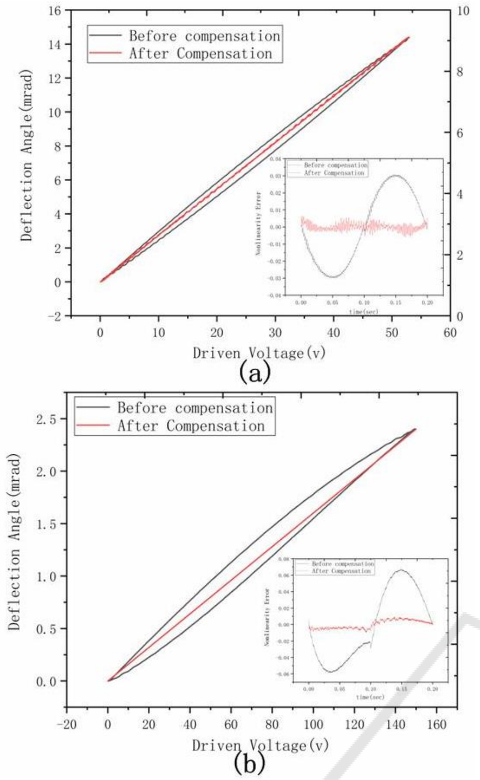

Figure 7: Scanning hysteresis loops of the scanner before and after compensation and the comparison of nonlinearities for X-axis and Y-axis.

waveform for Y-axis is much bigger than X-axis. Hence, the distortion in Fig. 6(b) is larger than Fig. 6 (a).

The hysteresis effect of the piezoelectric ceramic is originated from its inherent characteristics. In our previous work, a hysteresis compensation algorithm is introduced to restrain the hysteresis and proves its Effectiveness (Sweeney et al., R. 2002). Therefore, the algorithm is also applied to the scanner in this paper. As shown in Fig. 7, the nonlinearity produced by the hysteresis effect is reduced from 3% to 0.5% for X-axis and from 6% to 1%.

Some scanning images (Fig. 8) show single-axis scans and a 2D scan. The single-axis scans are very straight thus demonstrating the high linearity and low inter-axis interference of the scanner. The 2D image, produced with the x-axis driven by a 30-Hz sine waveform and the y-axis was driven by a 20-Hz cosine wave, shows a Lissajous-Figure.

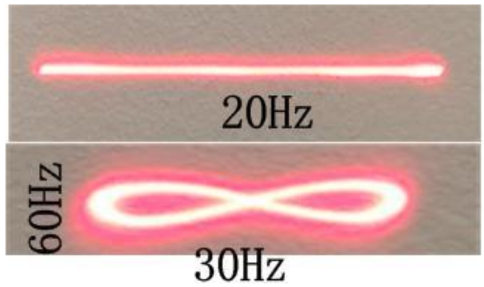

Figure 8: Scanning images of the scanner.

4 CONCLUSIONS

A compact new 2-D laser scanner based on piezoelectric actuators is designed, prototyped, and experimentally tested. The scanner proposed a novel mechanical structure to reduce the mechanical cross coupling ratio. Different from traditional 2-D laser scanner, it uses only 1-D flexible hinges to achieve 2-D deflection. A performance test system was built up to test the capabilities of the prototype scanner. In addition, a hysteresis compensation algorithm is applied to the scanner to improve the scanning linearity. From the test results, the scanner has a tilt angle of 43.19 mrad for X-axis with resonance frequency at 149.21 Hz and 2.41 mrad for Y-axis with resonance frequency at 232.59 Hz. Its scanning nonlinearity is reduced from 3% to 0.5% for X-axis and from 6% to 1%. Some actual scanning images are presented as well.

Some improvement of the scanner, such as structural optimization for the Y-axis and closed-loop control technology is undertaking to achieve larger scanning angle and higher accuracy.

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