A 3D Polymer Based Printed Two-Dimensional Laser Scanner

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Abstract. A two-dimensional (2D) polymer based scanning mirror with magnetic actuation is developed for imaging applications. Proposed device consists of a circular suspension holding a rectangular mirror and can generate a 2D scan pattern. Three dimensional (3D) printing technology which is used for implementation of the device, offers added flexibility in controlling the cross-sectional profile as well as the stress distribution compared to the traditional planar process technologies. The mirror device is developed to meet a portable, miniaturized confocal microscope application in mind, delivering 4.5 and 4.8 degrees of optical scan angles at 111 and 267 Hz, respectively. As a result of this mechanical performance, the resulting microscope incorporating the mirror is estimated to accomplish a field of view (FOV) of 350 $\mu$m x 350 $\mu$m.

1. Introduction

Miniaturization of the laser scanning microscopes to endoscopic imagers and hand-held probes necessitate shrinkage of the size of the scanning unit. Although, galvanometers are preferred as the scanning units in early and conventional laser scanning microscopes (LSM) [1], nowadays, the scanning units are getting replaced by micro-scanners in order to make the LSM more compact and portable [2, 3, 4].

These MEMS devices can be actuated using different kind of techniques such as electrothermal [5], electrostatic [6], piezoelectric [7], and electromagnetic [8] ones. MEMS based micro-scanners reported in handheld LSM system applications mainly use Si as the main fabrication material [9, 10].

The micro-scanners used in LSM systems have various topologies and been built using different kind of structural materials, in order to make them have better scanning angles, imaging and stress performance. The choice of fabrication material can also be used to make these micro-scanners as cheap as possible. Magnetically actuated Fire Resistant 4 (FR4) based micro-scanners that have been implemented for barcode scanning application are shown in literature [11]. Micro-scanners that use polymer as the structural material have been implemented for display applications [12].

Micro-scanner is located at the core of LSM and it is responsible for the two-dimensional orthogonal scanning. Even though various structural materials are present for fabrication,
a great majority of the micro-scanners were implemented using Si planar microfabrication processes that restrict shapes of cross-sectional profiles to rectangular ones, in turn limiting the mechanical performance. In order to acquire a high optomechanical performance, i.e. low-cost, low power micro-scanner with low stress distribution and long life time, we resort to a native 3D fabrication process, namely polymer 3D printing.

In this study, 3D printing technology is used to fabricate polymer based micro-scanner which can carry-out two dimensional orthogonal scan movement. Section 2.1 reports optical design and ray tracing simulations. Overview of the micro-scanner is demonstrated in a CAD environment and FEM simulations are conducted in Section 3. Fabrication of the device is briefly explained in Section 4.1 and experimental results are outlined in Section 4.2. Conclusion and discussions are supplied in Section 5.

2. Device Operation

2.1. Optical Design

In order to determine mechanical design constraints of the targeted 3D printed micro-scanner, we performed optical ray tracing simulations as shown in Fig. 1 along with theoretical calculations. The micro-scanner is positioned with inclination 45 degrees to the optical axis and the objective lens. For the targeted confocal microscopy application, we aim to achieve i) approximately 1 µm resolution for sub-cellular imaging capability and ii) 350 µm x 350 µm FOV that is comparable to state-of-the-art benchtop laser scanning microscopes. [2, 13].

![Figure 1. Optical ray tracing simulation for a confocal microscopy application.](image)

Off-the-shelf GRIN and miniaturized lenses to be used in LSM typically offer up to 0.5-0.6 NA [14] for the chosen wavelength of 650 nm, allowing tight focusing within limited volume. The choice of objective lens is made to accommodate an input beam size of 3.5 mm (in accordance with the mirror size of the micro-scanner) plus additional shift during scanning operation while providing the targeted 1 µm full-width-half-maximum (FWHM) lateral resolution. Therefore, we have considered an objective lens having 0.4 NA (large enough to produce desired resolution), 6.1 mm diameter (large enough to accommodate beam size and beam shift due to scanning) and 4.6 mm effective focal length (ensuring 0.4 NA). The lateral FWHM resolution is given [15]:
\[ w = \frac{2\sqrt{\ln 2}}{\ln 2} \cdot 0.32 \cdot \lambda \quad \text{(1)} \]

For a 3.5 mm wide input beam with an effective NA of 0.175 that is underfilling the lens having 0.4 NA, we achieve a FWHM lateral resolution of 0.87 \( \mu \)m. We invoke the paraxial approximation in order to relate the field of view (FOV) to the zero-to-peak optical scan angle \( \theta_o \) with the following equation.

\[ \text{FOV} = 2 \theta_o f \quad \text{(2)} \]

where \( f \) is the focal length of the objective. Therefore, in accordance with the desired FOV of 350 \( \mu \)m x 350 \( \mu \)m, one needs a zero-to-peak optical scan angle of 2.4 degrees, corresponding to a zero-to-peak mechanical scan angle of 1.2 degrees for the focal length of 4.6 mm. For the given optical architecture and beam size, the FWHM resolution and FOV were also simulated in a ray tracing environment and is observed to perfectly match analytical results as given in Fig. 1.

3. Mechanical Design & FEM Simulations

The device is completed satisfying the targeted constraints. It is constructed within a CAD tool. The cross-section of flexure is made circular to reduce the stress at the junction points. In order to use magnetic actuation, holes are opened to place small circular magnets having a diameter and thickness of 3 mm and 1 mm, respectively.

![Figure 2. Drawing of the micro-scanner parametrically showing its dimensions.](image)

The mode shapes and eigenfrequencies of the micro-scanner are obtained via finite element method simulations. Before the fabrication process, finite element simulation results give a rough idea about the resonant frequencies of the corresponding mode shapes of the micro-scanners.

Structural material of the micro-scanner device is VeroClear has a manufacturer specified density \( \rho_v = 1045 \text{ kg/m}^3 \) and Young’s Modulus \( E_v = 2 - 3 \text{ GPa} \) making it a suitable material for low-frequency resonant actuators. In order to model the micro-scanner in finite element simulations, \( E_v \) is set to 2.5 GPa and Poisson’s ratio \( \nu_v \) is assumed to be 0.35 for VeroClear material, which lies in the natural range for polymers. Moreover, the magnets attached to the device are made of Neodymium which has a density \( (\rho_n) \) of 7500 kg/m\(^3\), Young’s Modulus \( (E_n) \)
Table 1. Dimensions of the micro-scanner. (all in mm)

| $D_t$ | $L_t$ | $L_c$ | $L_1$ | $W_c$ | $W_1$ | $W_2$ | $t_c$ | $L_h$ | $t_h$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1     | 8     | 12    | 8     | 8     | 2.5   | 1.75  | 2     | 3     | 1     |

Figure 3. Out-of-plane bending at 137 Hz.

Figure 4. Torsion at 335 Hz.

of 160 GPa and a Poisson’s ratio ($v_n$) of 0.24. The mode shapes for the movement of the micro-scanner are shown in Fig 3, 4. The combination of the second and the third modes are used to get Lissajous patterns. The second mode of the micro-scanner is out-of-plane bending movement at 137 Hz (Fig 3). Torsion, which is the third mode, around the flexure is observed at 335 Hz (Fig 4).

4. Experimental Results

4.1. Fabrication

3D model designed in a computer-aided-design sofware is exported to the 3D prints. The next step is converting these solid structures into series of thin slices to be physically fabricated layer by layer. Liquid photopolymer material (VeroClear) is selectively exposed to a UV light source, causing it to cure into a solid object. Small neodymium magnets are sticked with epoxy resin as shown in Fig. 5.

Figure 5. Polymer based 3D printed micro-scanner with attached permanent magnets.

Figure 6. Frequency response of the micro-scanner for varying electrocoil current drives.
4.2. Measurement Results
A characterization setup, which includes an oscilloscope (Tektronix TDS 3032B), signal generator (Tektronix AFG 3101), laser doppler vibrometer (LDV) (Polytech OFV 2500), and PC is used to measure the frequency responses of the micro-scanner. The dynamic deflection of the micro-scanner as a function of frequency is shown in Fig. 6. The electro-coil is fed with a constant sinusoidal amplitude and by varying frequency of the signal, the vibration velocity values are collected by the LDV in ambient air.

As seen in Fig. 6 the slow resonance peaks of the micro-scanner corresponds to the out-of-plane bending mode are at 127 Hz. At this frequency, micro-scanner generate maximum deflections of $32 \mu m$ for a 34 mA current. Moreover, quality factor of the device is around 31 for the out-of-plane movement. Torsion around the flexure is observed at 274 Hz. At this frequency, micro-scanner generate maximum deflection around $2.4 \mu m$. Furthermore, quality factor of the micro-scanner is around 25 for the torsion.

4.3. Experimental Lissajous Pattern
Laser source having a wavelength of 650 nm is directed toward the micro-scanner. Lissajous pattern has a length of 14 and 15 mm in vertical and horizontal axes while the coil is fed with a constant current of 64 mA as shown in Fig. 7. This image is occured at a distance of 358.2 mm away from the scanner, hence, TOSA of the scanner for the vertical and horizontal axes are 4.5 and 4.8 degress which meets the desired FOV.

![Figure 7. Lissajous patterns obtained at a distance of 358.2 mm from the scanner. The driving frequencies are 111 and 267 Hz for vertical and horizontal axes, respectively.](image)

5. Conclusions and Discussions
First of all, optical ray tracing simulations of a micro-scanner is performed to determine the mechanical constraints to integrated this device in a confocal system. In order to have 1 $\mu m$ resolution and 350 $\mu m$ x 350 $\mu m$ for a 3.5 mm input beam with an effective NA of 0.175 which fulfils an objective lens having 0.4 NA and focal length of 4.6 mm, one need a micro-scanner to utilize zero-to-peak mechanical scan angle of 1.2 degrees.

For this purpose, a 3D-printed micro-scanner is designed, simulated and characterized. Thanks to the 3D printing technology, flexure of the device is made circular to reduce the stress distribution on the flexure. To further optimize the micro-scanner, it is also possible to engineer the shape of the device in all three dimensions. In order to achieve magnetic actuation, small magnets are attached to the device. FEM simulations reveal that the designed structure makes
out-of-plane bending movement and torsion at 137 and 335 Hz, respectively. Frequency response data of the micro-scanner is acquired via an LDV. The out-of-plane bending and the torsion mode is observed at 127 and 274 Hz, respectively. TOSA of the micro-scanner is measured for the vertical and horizontal axes and are found to be 4.5 and 4.8 degrees.

6. References
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