Published in final edited form as:

Opt Eng. 2016 January ; 55(1): . doi:10.1117/1.OE.55.1.013104.

Development of tunable miniature piezoelectric-based scanners validated by the combination of two scanners in a direct image relay technique

Adam Harbi Shadfan^a, Michal Emanuel Pawlowski^a, and Tomasz S. Tkaczyk^{a,b,*}

^aRice University, Bioengineering Department, 6100 Main Street, Houston, Texas 77005-1892, United States

^bRice University, Electrical and Computer Engineering Department, 6100 Main Street, Houston, Texas 77005-1892, United States

Abstract

Miniature piezoelectric actuators are commonly used as a compact means to relay images for numerous endoscopic applications. These scanners normally consist of an electrically driven lead zirconate titanate (PZT) tube that oscillates an optical fiber at its resonant frequency. The diameter and length of the PZT and fiber, the attachment of the fiber to the PZT, as well as the driving signal determine the main characteristics of the scan—frequency and amplitude of vibration. We present a new, robust, and repeatable method for producing miniature PZT actuators. The described technology allows for continuous tuning of the scanner mechanical properties during the assembly stage, enabling adjustment of resonant frequency and subsequent amplitude of vibration without a *priori* knowledge of the fiber's mechanical properties. The method consists of manufacturing high-precision fiber-holding plastic inserts with diamond turning lathes that allow for the fiber length to be quickly varied and locked during operation in order to meet the preferred performance. This concept of tuned PZTs was demonstrated with an imaging technique that combined two scanners oscillating in unison at the ends of a single optical fiber to relay images without the need to correlate the driving signal with a detector.

Keywords

optical scanning; micromachining; diamond machining; dual scanning imaging; endoscopy

1 Introduction

Endoscopy procedures allow for the examination and interrogation of internal structures and functions through the use of small optical devices introduced into a cavity of the body. Endoscopy is often employed to observe and treat conditions associated with gastrointestinal and respiratory tracts, such as esophageal adenocarcinoma, Barrett's esophagus, colorectal cancer, Crohn's disease, and many others,^{1,2} and has also been proven useful to aid in middle-ear surgery³ as well as microsurgery outside the body.⁴ In order to minimize

*Address all correspondence to: Tomasz S. Tkaczyk, Ttkaczyk@rice.edu.

discomfort to a patient, lead zirconate titanate (PZT) actuators are commonly used in endoscopes to relay light to and from difficult to access organs and areas in a compact form. An alternative commonly used strategy to reduce the size of the device is to incorporate a fiber bundle as an image guide. While beneficial for not requiring any moving components, fiber bundles lack flexibility with a poor bend radius compared to a single-mode fiber as used in a PZT system. The bundles additionally suffer from reduced lateral optical resolution due to the pixilation effect and crosstalk between adjacent fiber cores.⁵ A PZT system provides the opportunity of building a miniaturized device with a larger field of view and greater achievable optical resolution than a system utilizing static optical components in a more compact form. Additionally, miniaturization of the distal end optics reduces discomfort to patients and allows for the exploration of small bodily orifices for observation of luminal organs and tissues. For example, miniature PZTs have been utilized in endomicroscopy to provide widefield full-color imaging,⁶ three-dimensional (3-D) optical coherence tomography imaging,^{7,8} two-photon fluorescence imaging,⁹ confocal imaging,¹⁰ and to increase the ablation region of laser surgical probes.¹¹ Confined to a few millimeters in diameter (between 2.7 to 4 mm in middle-ear probes¹² and typically <5 mm for endomicroscopic systems), these probes typically consist of a miniature lens to focus light onto a PZT-controlled optical fiber, which is vibrated at its resonance frequency in order to image an area as defined by the actuator deflection, fiber mechanical properties, and imaging optics. The image reconstruction strategy, algorithm, and technique depend on the imaging modality employed by the scanner.^{7,9,10,13} For most systems, the light leaving the optical fiber is focused onto a point detector and is converted to an electrical signal. Using the known coordinates of the scan at each point, which is typically either a spiral or a Lissajous pattern depending on the driving signal, a reconstruction algorithm assigns the voltage of the signal to a pixel as an intensity value.¹⁴ The image is then smoothed across the field using interpolation of nearby pixels. The reconstructed image often requires further postprocessing with distortion removal with a remapping algorithm.^{10,13,14}

While there have been numerous examples of PZT miniature scanners, rarely are the details of the mechanical design of the scanner fully reported. Li et al.¹⁵ previously described the effects of the choice of fiber, fiber length, and PZT size on resonant frequency and scanning range by producing eight different fixed scanners. One step of the fabrication process that is critical for defining the performance of a PZT-based scanner is the design of the mechanical attachment binding the optical fiber to the PZT. Most reported solutions for fixing the fiber to the PZT calls for the nondescriptive use of an adhesive, permanently setting the parameters of device.^{7,13,15,16} This technique has been proven to produce repeatable results.¹⁵ More recently, groups have utilized solutions that provide a greater degree of tunability through the inclusion of either mounted heads,⁸ pinholes epoxied to hypodermic tubes,¹⁷ or silicon fiber holders.¹⁰ The silicon fiber holder offers very tight tolerances, with measured deviations of <5 μm of the pinhole on axis from the design.¹⁸ Meinert et al.¹⁰ relied on tuning through the use of a liquid lens and did not report on variability of the fiber length once placed inside the mount. In this paper, we present a robust and repeatable method for manufacturing tunable PZT scanners based on the production of high precision fiber holding poly(methyl methacrylate) (PMMA) inserts through the use of optical grade diamond turning lathes to achieve interference fit tolerance to the PZT tube. A miniature

drill bit is used to drill an on axis hole in the insert to maintain the fiber length due to friction restraining the fiber's axial movement. The interference fit between the fiber and the insert allows the user to adjust the fiber length during testing. The reported process allows for the testing of the parameters of the assembly before an epoxy is applied and does not increase the size of the probe. Additionally, due to the low Young's modulus of the PMMA, the system can be disassembled and reassembled reliably without the need for specialized tools or training. With this assembly process, it is possible to experimentally adjust the scanner characteristics by varying the fiber length extended from the PZT and even replace the fiber without risk of damaging the components in order to meet the desired performance for the user and application.

To prove the repeatability and robustness of the manufacturing process, we have fabricated and combined two identical scanners into an imaging system that relays an image between the distal and proximal ends of an optical system via two synchronized PZT scanners without the need for image processing that is required in systems utilizing a single scanner coupled with a nonpixelated light detector. Both PZTs oscillate in phase, identically rotating the shared fiber at either end, resulting in acquisition of two-dimensional (2-D) images without the need to correlate the scanner-driving signal with the image detector. This new imaging method allows for direct image relay, which could prove useful when it is difficult to utilize electronic components in order to display images recorded by an endoscope. By relying exclusively on the hardware without any postprocessing, the optical performance of this new system depends on the scanning characteristics of the two PZTs, which can be tuned to desired specifications. The dual scanning setup presented employs a transillumination subsystem designed to observe transparent samples. We would like to note that other imaging modalities may benefit from the use of the presented technology, albeit the optomechanical setup may be more complex with illumination through the fiber in a reflectance mode. We envision future applications of this technology to build reliable and predictable PZT scanners for a variety of applications ranging from microendoscopy to optical coherence tomography⁷ to display technology.¹⁹

2 Piezo Manufacturing

Typically, a PZT scanner consists of the optical fiber, the ceramic actuator, an epoxied mount to hold the fiber, and a voltage driver. Electric leads are soldered on to the activated quadrants of the PZT and the fiber is permanently attached to the PZT. Time-modulated voltage is applied to the driver at the resonant frequency of the system, and an image is reconstructed by correlating the PZT motion with the recorded intensity signal. In most published works, the fiber is permanently attached to the PZT, preventing further tuning or modification of the system's characteristic resonant frequency.

2.1 Fiber-Holding Poly(methyl methacrylate) Insert

There are two mechanical components that affect the quality and reliability of a PZT scanner—a holder that sets the position of a scanner within the system enclosure and a mount that fixes the position of the base of a fiber tip cantilever in reference to the PZT tube. The holder that sets the position of the scanner is critical to system reliability. A mount that holds the

base of the fiber cantilever has a direct influence over the resonant frequency of the system. Both mounts should be as secure as possible, maintaining the positioning while at the same time allowing the PZT tube to vibrate. Typically, glue is used for both mounts. While strong and simple to apply, glued connections are not adjustable and as a result, the position of the scanner relative to the mount and the resonant frequency cannot be changed. While it is theoretically possible to match resonant frequencies of two independently manufactured scanners using glued connections, such a process may be very difficult and costly. Rather than relying exclusively on an adhesive as the basis of the mount, we propose a solution that utilizes a plastic interface component referred to as a fiber insert. The insert is a plastic cylinder with an axial hole [an example of a PZT insert is depicted in Fig. 1 (a)]. The outer diameter of the cylinder is manufactured to conform to tight interference fit tolerance with the inner diameter of the PZT tube. The overlapping external diameter of the rod and internal diameter of the PZT tube provide (due to the slight deformation of the plastic insert) enough clamping force to hold the insert at the end of the PZT scanner [Fig. 1 (a)]. The axial hole is designed to guide a fiber optic cable, with the diameter chosen in such a way that friction between the internal walls of the insert and the external protective coating of the fiber immobilizes the fiber during oscillation while still allowing the operator to adjust the fiber length during the assembly and tuning stage. For the purpose of the experiments presented herein, we used an optical fiber model 780HP (Thorlabs, Newton, New Jersey), with a $5.0 \pm 0.5 \mu\text{m}$ mode field diameter, a $125 \pm 1.5 \mu\text{m}$ cladding diameter, a $245 \pm 0.5 \mu\text{m}$ coating diameter, and a numerical aperture of 0.13 at 780 to 970 nm. A diagram of the proposed scanner can be seen in Fig. 1 (b).

2.2 Poly(methyl methacrylate) Insert Fabrication

We manufactured the PZT inserts from PMMA on two Optimum 2400 (Precitech, Keene, New Hampshire) diamond turning lathes. The external, cylindrical surface is manufactured using standard, diamond turning tools intended for the processing of plastic optics. The internal, axial orifice is drilled on the diamond turning machine with a miniature drill from the MSE00XXSB series (Mitsubishi, Tokyo, Japan), where XX is the drill diameter expressed in tens of micrometers. For example, the primary drill used in this work was MSE0024SB, corresponding to a diameter of 240 μm . Precision diamond turning allows us to control the outer shape of the insert with nanometric precision. The inherent properties of the drilling process (namely, the removal of the processed material using relative rotational motion of the tool in regard to the processed part) combined with the corkscrew-like shape of the outer cutting surface of the drill does not allow for precise control of a diameter of the drilled hole, as the chips of processed material are pressed against the walls of freshly processed hole during their outward movement. For that reason, drilled holes are usually measurably larger than the diameter of drills used to manufacture them. For our application, the guiding hole diameter together with the fiber outer diameter should conform to tight, transition fit tolerances. Typically, tightly tolerated holes are manufactured in a two stage process. In the first step, a hole is drilled with a sub-diameter drill. In the second step, the remaining small amount of excess material is removed by a dedicated reamer, which has a tightly tolerated outer diameter and leaves a smooth, precision machined inner surface. In our case, where the target hole diameter must match the fiber outer diameter with submillimeter precision, reamers are not available in the required sizes. We relied instead on

the repeatability of a precise drilling process, by using material from only one manufacturing batch and by tightly controlling process parameters: the relative speeds of the tool and the processed part, rotation of the part, and the feed rate. To match the diameter of the fiber, we tested a range of drills of different diameters spanning from 100 to 400 μm . We have found experimentally that a drill with a diameter of 240 μm allowed us to manufacture a hole that matched an outer 260 μm diameter of the 780HP single-mode fiber used in this work. The manufacturing process of the PZT insert takes an operator about 2 h, consisting of diamond turning the PMMA rod to match the diameter of the PZT and drilling the insert. A short video showing the insert drilling process is depicted in an attached video (Video 1) with a still image from the video in Fig. 2. Note that the use of the ultraprecision diamond lathe typically used for prototyping optical components produces optical quality surfaces as displayed in Video 1, with surface roughness between 5 and 10 nm.

In order to minimize the dimensions of the scanning system, we have used EBL #2 PZT tubes (EBL, Piezoelectric Precision, East Hartford, Connecticut) as the actuator. EBL #2 PZT tubes have an outer diameter of 1.98 mm and inner diameter of 0.2921 mm. Their inner diameter is loosely controlled during the manufacturing stage, necessitating single actuator-specific PMMA inserts to be manufactured.

2.3 Complete Lead Zirconate Titanate Scanner Assembly

In order to demonstrate the tunability of this manufacturing process, two complete, matching PZT scanners were produced. The process began with the fabrication of the inserts from PMMA rods. Both inserts were then drilled to fit the 780HP optical fiber. Five electrical leads were soldered onto the PZTs in order to control the movement with a voltage driver. The five electrodes of the PZT were ground, North, South, East and West. A machineable-fast set epoxy (Hardman, Belleville, New Jersey) was applied at the proximal end of the PZT actuator, in order to protect the electrical leads and provide a scanner mounting point. An image of the two scanners with epoxy applied over the electrical contacts can be seen in Fig. 3. The epoxy was diamond turned to fit the 5.0-mm inner diameter of a hypodermic tube that could be held in place by standard optical benchtop mounts. Assembling the scanner consisted of placing the fiber into the insert, followed by friction mounting of the PMMA insert within the PZT actuator. Finally, the PZT cylinder was mounted with the hypodermic tube.

3 Custom Voltage Amplifier

Both PZT actuators are driven by custom built voltage amplifiers. We used one four-channel amplifier to drive each PZT tube. The voltage amplifiers were built around E02CT (EMCO High Voltage, Sutter Creek, California) proportional DC to DC converters, that power four operational amplifiers (AMPEX PA97DR, AMPEX Microtechnology, Tucson, Arizona), configured to provide a $10\times$ gain. The operational amplifiers are controlled by a logical signal from a PCIe-6353 (National Instruments, Austin, Texas) analog/digital (A/D) input output (I/O) card. The driving system is able to provide PZT driving signal in the range of ± 100 V in response to ± 10 V logical signals from the NI I/O card. The PZT tube contacts are logically divided into ground, North, South, East, and West. In order to maximize

deflection of the PZT tube, North–South and East–West pairs are driven by signals of the same amplitude and opposite polarity. That way, when one side of the PZT tube shrinks due to applied voltage, the opposite side expands, forcing the fiber tip cantilever to oscillate. We created a custom LabView (National Instruments, Austin, Texas) program to independently control both PZT actuators. The developed application allows us to independently control driving signal shape, amplitude, frequency, and relative phase between all four channels of both PZT actuators.

4 Tuning of Lead Zirconate Titanate Response

For our imaging applications involving PZT scanners, we are interested in the resonant frequency in order to maximize the field of view either illuminated or observed. As has been described in previous publications, the resonant frequency of the PZT is determined by the geometry of the cantilever tip (optical fiber) while the scanning range depends on both the cantilever and PZT size.^{9,15,16,20} It has been shown that the resonant frequency of the fiber can be theoretically calculated as

$$f = \frac{\pi \sqrt{E}}{16 \sqrt{\rho}} \frac{R}{L^2} B_n^2, \quad (1)$$

where E is the Young's modulus, ρ is the density of the fiber, R is the radius of the fiber, L is the fiber length, and B_n is a numerical constant equal to 1.194, 2.988,¹⁶ Without changing any parameters besides fiber length L , we can expect an inverse correlation with resonant frequency. In the proposed solution herein, the PMMA insert is immobilized with the actuator due to the elastic deformation of the PMMA material originating from the interference fit tolerances between the internal diameter of the PZT and external diameter of the insert. Similarly the fiber is held by the insert, and as a result, this solution provides the ability to modify the resonant frequency of the system. Because the fiber cantilever length affects both the resonant frequency and the amplitude of vibration, we have the ability to experimentally tune each PZT scanner to a desired frequency and amplitude of vibration without the need to theoretically predict the system behavior using Eq. (1) based on assumed parameters of the actuator. This approach is practical when the properties and tolerances of the components of the complete PZT scanner assembly are not well defined or fully reported. One of the strengths of this system is the ability to observe the effects of changing the fiber length without needing to disassemble the entire probe, allowing the user to find the optimal parameters for the application.

4.1 Experimental Tuning of Lead Zirconate Titanate Resonant Frequency and Vibrational Amplitude

In order to tune the scanning performance of both PZTs, a CCD camera was used to observe the range of deflection as the fiber length extending from the insert was varied. For the experimental setup (Fig. 4), the PZTs share a single fiber (780HB) that is illuminated on the proximal end and imaged on the distal side. Each PZT has its own independent driver that can be synchronized with each other. Two 0.1 NA commercial objectives are mounted back

to back to each other in order to provide $1\times$ magnification, in an effort to provide additional spacing between the object to be imaged from potentially contacting the moving fiber. A 1951 United States Air Force negative resolution target was imaged by the dual scanning system, which was illuminated by a halogen lamp passed through a 731-nm filter. For this setup, the theoretical limit of resolution according to the Rayleigh criterion calculated for a 0.1 NA objective should be $4.46\text{ }\mu\text{m}$, with the ability to resolve the bar patterns between elements 5 and 6 of group 7. For the initial fiber length varying experiments of each PZT, the resolution target was removed from the setup. Rather than requiring a point detector like most PZT imaging systems, this imaging method utilizes a CCD camera to image directly.

To begin assessing the performance of each scanner, all operating conditions including applied voltage and mounts were kept the same, with only the fiber length varied. For initial measurements, the fiber length was set to 20 mm and a driving cosine signal was sent to the north–south electrodes of the first PZT at a frequency of 150 Hz and voltage amplitude of $\pm 50\text{ V}$. The driving signal can be described with the following equation:

$$x(t) = A \cos(2\pi ft + \varphi), \quad (2)$$

where x is the displacement in time (t), A is the voltage amplitude, f is the driving frequency, and φ is the phase shift. These operating parameters are comparable to a similarly sized PZT.⁹ To find the maximum displacement, the frequency was swept across a range from 50 to 1500 Hz, allowing for observation of both the first and second mode resonances. The experiments were repeated for the east–west electrodes and at varying lengths (15, 10, 9, and 7 mm). As expected, it was observed that a longer fiber resulted in a larger deflection, at the cost of a smaller resonant frequency, ranging from a deflection of $\sim 350\text{ }\mu\text{m}$ down to $100\text{ }\mu\text{m}$ and a frequency of 175 Hz up to 1300 Hz, respectively. For imaging applications, a compromise must be made to provide the largest field possible with highest scan frequency for fast imaging rates. With the ability to scan $140\text{ }\mu\text{m}$ at ~ 920 and 880 Hz in each direction, a fiber length of 9 mm, measured from the face of the insert, was selected for the rest of the experiments, providing sufficient scanning speed and field of view, which could be increased by applying a larger voltage (up to $\pm 100\text{ V}$). The scans at different fiber lengths and the associated change to resonant frequency and deflection size can be seen in Fig. 5.

As shown in Fig. 5, slight irregularities to the scan pattern in each direction were observed (oval pattern instead of straight lines). This behavior was expected due to the low amount of friction between the fiber coating and PMMA insert. While elliptical oscillation of the fiber cantilever is not desirable, the irregularity can be simply removed through the application of a small amount of glue to securely fix the fiber to the insert. The application of the epoxy is performed after the tuning process is complete and desirable parameters have been met. Images of the scan before and after the application of the epoxy can be seen in Fig. 6, along with the slight change in resonant frequency that was observed as the mass and length slightly changed. After five separate iterations, we observed that the change to the resonant frequency was reliably within 150 Hz as compared to the initial resonant frequency. The small differences in amplitude of vibration at the frequency at which the PZTs are driven were compensated by adjusting the amplitude and phase of the driving signal.

Last, it should be noted that the fiber continues to oscillate with a full width at half maximum (FWHM) bandwidth of ± 30 Hz of the resonant frequency. The FWHM of the bandwidth is nominally determined by the quality factor (Q-factor), which is an indication of how well mechanical energy is stored.⁷ Roughly measured by the ratio of resonance frequency to bandwidth, the Q-factor can be improved by reducing the resonant frequency and bandwidth with the addition of a cantilever weight.^{7,8,20} However, for this application in which we are trying to match two scanners, a larger bandwidth is preferred. The slight differences in frequency that can arise due to manufacturing imperfections can thus be corrected by changing the operating parameters (driving frequency, voltage, and phase) of each independently controlled PZT in order to synchronize movement of both fiber cantilevers. Lissajous scanning further negates the issue of slight differences in resonant frequencies between north–south and east–west poles, as the pattern is created by vibrating the poles at different frequencies, where the ratio of the frequencies and amplitude between the two directions defines the filling density and coverage of the Lissajous pattern.²⁰

5 Dual Scanning Imaging

In order to assess the ability of our manufacturing process to tune the two PZTs for synchronized operation, the PZTs were driven to vibrate the distal and proximal ends of a single shared fiber at the same operating frequencies in order to relay an image without the need for image processing that is required in systems utilizing a single scanner coupled with a nonpixelated light detector. With both PZTs oscillating in phase in order to identically rotate the shared fiber at either end, 2-D images are acquired without the need to correlate the scanner-driving signal with the image detector. With the length of fiber protruding from both scanners set to 9 mm, the voltage amplifiers drove each PZT to produce identical Lissajous patterns. The Lissajous pattern was produced by driving one of the electrode pairs with a cosine function with an amplitude of ± 50 V at a frequency of 1020 Hz while the second pair was vibrated at 985 Hz and ± 50 V for both PZTs. In order to accurately synchronize the two PZTs, a phase adjustment between PZT1 and PZT2 is necessary in order to account for irregular shifts caused by manufacturing imperfections. With the operating parameters set, the resolution target was placed in the focal plane of the microscope objective based image relay system (Fig. 4) and images of the target were acquired. Figure 7 depicts a series of images of a number “2” feature from the resolution target recorded during the synchronization of the dual PZT system. The image on the far left shows the blurred number “2” recorded when vibrating each PZT at the same frequency without synchronization of the relative phase of the driving signals. As the relative phase between both the north–south and east–west poles of PZT1 is slowly modified to match the movement of PZT2, the image of the number “2” becomes sharper. A video of the effect of the phase change can be found in Video 2.

With the phase matched correctly, images with a field of view of $100 \times 100 \mu\text{m}^2$ were recorded separately while the resolution target was translated across the face of first PZT. Under the chosen operating conditions (which can be varied), the imaging system was able to resolve at least the individual elements from group 5, element 6, where a single bar corresponds to a value of $8.7 \mu\text{m}$. A video of the images acquired while the resolution target

was translated across the PZT can be seen in Video 3, with several frames arranged into the known position shown in the Fig. 8(a) along with the corresponding reference target (b).

Varying the amplitude and adjusting the frequency to account for the change in the filling of the Lissajous pattern, the field of view could be changed. By increasing the voltage up to ± 100 V and adjusting the frequencies to 1015 and 995 Hz, the field of view was increased $\sim 125\%$ to $225 \times 225 \mu\text{m}^2$. Again, the resolution target was translated across the PZT while several frames were taken (Video 4). Select frames over the field can be seen in Fig. 9, with a comparison to the reference target. Of note, there is an expected drop off in achievable resolution due to loss of synchronization of the PZTs with the camera acquisition settings. Specifically, the system resolution can be manipulated by changing the driving voltage and frequency while maintaining a camera exposure time of 185 ms. The expected resolution thus worsens as the field of view is increased.

In order to show the improvement in resolution, the applied voltage was decreased down to ± 35 V and frequencies further from the resonant frequency were selected (1020 and 970 Hz) without changing the camera parameters. With a scanning field of view of only $50 \mu\text{m}$, due to a smaller applied voltage, the dual scanning system was able to resolve at least group 7, element 1, as seen in Video 5 with select frames displayed in Fig. 10, corresponding to a single line width of $3.91 \mu\text{m}$.

The image distortion observed in this proof of concept system is most likely due to differences in electrical and mechanical properties of the PZT actuators and assembly imperfections. The PZTs used in this work have small shape differences, which required us to manufacture nonexchangeable PMMA inserts for each PZT. Additionally, the assembly setup did not allow for precise control of the angular orientation of the PZT cantilever in reference to the PZT tube. While we corrected the vibrational response of both scanners, we had limited control over miniscule differences in motion between the moving cantilevers. We believe that proper selection of components and tighter control of assembly stage may improve the quality of images obtained in a dual PZT scanning setup, which we plan on pursuing further.

These initial results illustrate the tunability of PZT scanners built with diamond turned, microdrilled inserts and the ability to synchronize the scanning performance through the correction of electromechanical differences. To the best of our knowledge, this is the first dual PZT system that is able to relay images without the need for a 2-D display or synchronization between the imaging detector and PZT actuator.

6 Conclusions

The development of custom fitted plastic inserts to fit and hold an optical fiber with a PZT scanner allows for a great degree of tunability. With limited knowledge of the mechanical properties of the individual components of a PZT scanner that can differ due to manufacturing processes, one can rapidly build a scanner that would meet the desired scanning parameters by tuning the fiber cantilever length. Additionally, using the presented technology, during the adjustment stage, it is possible to simply disassemble the system in

order to replace PZTs, inserts, or fibers in order to match desired performance, assuming mechanical compatibility. With a manufacturing time of 2 h, one can afford to test a single PZT actuator with multiple fibers. This degree of tunability should aid in the rapid manufacturing of endoscopic systems with single or multiple scanners. This tunability was verified by the synchronized performance of two PZTs, which could relay an image without the need for any reconstruction or postprocessing. The optical performance of this system depends on the chosen scanning parameters and can be experimentally adjusted to meet the desired performance. With the inclusion of a miniature objective, an endoscope can be built for a variety of applications including observation and disease diagnosis of the gastrointestinal or respiratory tracts, visualization of luminal organs, as well as a probe to perform ablation microsurgery.

Acknowledgments

Research reported in this publication was supported by the National Cancer Institute of Biomedical Imaging and Bioengineering under Award Number R21EB015022. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. Additionally, this work was supported by the Cancer Prevention & Research Institute of Texas (CPRIT) under award number RP130412.

References

1. Valdastrì P, Simi M, Webster RJ III. Advanced technologies for gastrointestinal endoscopy. *Annu. Rev. Biomed. Eng.* 2012; 14(1):397–429. [PubMed: 22655598]
2. Than TD. A review of localization systems for robotic endoscopic capsules. *IEEE Trans. Biomed. Eng.* 2012; 59(9):2387–2399. [PubMed: 22736628]
3. Kozin ED, et al. Systematic review of outcomes following observational and operative endoscopic middle ear surgery. *Laryngoscope.* 2015; 125(5):1205–1214. [PubMed: 25418475]
4. Hoy CL, et al. Clinical ultrafast laser surgery: recent advances and future directions. *IEEE J. Sel. Top. Quantum Electron.* 2014; 20(2):242–255.
5. Flusberg BA, et al. Fiber-optic fluorescence imaging. *Nat. Methods.* 2005; 2(12):941–950. [PubMed: 16299479]
6. Lee CM, et al. Scanning fiber endoscopy with highly flexible, 1 mm catheterscopes for wide-field, full-color imaging. *J. Biophotonics.* 2010; 3(5–6):385–407. [PubMed: 20336702]
7. Moon S, et al. Semi-resonant operation of a fiber-cantilever piezo-tube scanner for stable optical coherence tomography endoscope imaging. *Opt. Express.* 2010; 18(20):21183–21197. [PubMed: 20941015]
8. Park HC, Seo YH, Jeong KH. Lissajous fiber scanning for forward viewing optical endomicroscopy using asymmetric stiffness modulation. *Opt. Express.* 2014; 22(5):5818–5825. [PubMed: 24663919]
9. Do D, Yoo H, Gweon DG. Fiber-optic raster scanning two-photon endomicroscope using a tubular piezoelectric actuator. *J. Biomed. Opt.* 2014; 19(6):066010. [PubMed: 24972358]
10. Meinert T, et al. Varifocal MOEMS fiber scanner for confocal endo-microscopy. *Opt. Express.* 2014; 22(25):31529–31544. [PubMed: 25607103]
11. Ferhanoglu O, et al. A 5-mm piezo-scanning fiber device for high speed ultrafast laser microsurgery. *Biomed. Opt. Express.* 2014; 5(7):2023. [PubMed: 25071946]
12. Presutti, L., Marchioni, D. Chapter 1 in *Endoscopic Ear Surgery: Principles, Indications, and Techniques*. 1st. Germany: Thieme, Stuttgart; 2014. Starting off with endoscopic ear surgery; p. 1-4.
13. Seibel EJ, Johnston RS, Melville CD. A full-color scanning fiber endoscope. *Proc. SPIE.* 2006; 6083:608303.
14. Seibel EJ, et al. Prototype scanning fiber endoscope. *Proc. SPIE.* 2002; 4616:173.
15. Li Z, Yang Z, Fu L. Scanning properties of a resonant fiber-optic piezoelectric scanner. *Rev. Sci. Instrum.* 2011; 82(12):123707. [PubMed: 22225224]

16. Lee CM, et al. Scanning fiber endoscopy with highly flexible, 1 mm catheterscopes for wide-field, full-color imaging. *J. Biophoton.* 2010; 3(5–6):385–407.
17. Zhang N, et al. Compact piezoelectric transducer fiber scanning probe for optical coherence tomography. *Opt. Lett.* 2014; 39(2):186. [PubMed: 24562102]
18. Weber N, Zappe H, Seifert A. A tunable optofluidic silicon optical bench. *J. Microelectromech. Syst.* 2012; 21(6):1357–1364.
19. Hua WS, et al. Development of 2D microdisplay using an integrated microresonating waveguide scanning system. *J. Intell. Mater. Syst. Struct.* 2011; 22(14):1613–1622. [PubMed: 22876080]
20. Wu T, et al. Two-dimensional scanning realized by an asymmetry fiber cantilever driven by single piezo bender actuator for optical coherence tomography. *Opt. Express.* 2009; 17(16):13819–13829. [PubMed: 19654788]

Biographies

Adam Harbi Shadfan is a PhD candidate in the biomedical engineering department at Rice University. He received his BS degree in biomedical engineering from Texas A&M University in 2011. He works in the Tomasz Tkaczyk optics lab. His current research interests include optical design, instrumentation, and diagnostics.

Michal Emanuel Pawlowski received his MSc Eng. in applied optics from Warsaw University of Technology in 1997 and received his PhD from the same university in 2002. He was a postdoctoral student at the University of Electro-Communications in Tokyo between 2003 and 2005. Currently, he works at Rice University as a research scientist, where his main interests are applied optics, optical design, and bioengineering.

Tomasz S. Tkaczyk is an associate professor of bioengineering and electrical and computer engineering at Rice University. His research is in microscopy, endoscopy, cost-effective high-performance optics for diagnostics, and snapshot imaging systems. He received his MS and PhD degrees from the Institute of Micromechanics and Photonics, Warsaw University of Technology. In 2003, he began working as a research professor at the College of Optical Sciences, University of Arizona. He joined Rice University in 2007.

Fig. 1.

(a) Photograph of an optical fiber held by a microdrilled PMMA insert mounted in a lead zirconate titanate (PZT) tube. (b) Schematic of the proposed completed scanner consisting of (1) the fiber, (2) the PMMA insert, (3) the PZT tube, (4) machinable epoxy, and (5) soldered leads.

Fig. 2.
Still image from Video 1 (MOV, 3.16 MB [URL: [http://dx.doi.org/ 10.1117/1.OE.55.1.013104.1](http://dx.doi.org/10.1117/1.OE.55.1.013104.1)]). PZT insert drilling process.

Fig. 3.

(a) Two PZT scanners with inserts and soldered leads covered in epoxy. (b) Turned down diameter of a single scanner in front of a penny.

Fig. 4.
The optical layout of the imaging system, providing $1\times$ magnification before PZT1. The two PZTs on the right share a single 780HB fiber.

Fiber Length	North-South Scan (Resonant Frequency)	East-West Scan (Resonant Frequency)
20 mm	175 Hz	175 Hz
15 mm	327 Hz	318 Hz
10 mm	620 Hz	600 Hz
9 mm	920 Hz	880 Hz
7 mm	1310 Hz	1310 Hz

Fig. 5.

The changes to amplitude and resonant frequency due to the changing of the length of the optical fiber in the PZT scanner. Scale bars correspond to 100 μm .

Fig. 6.

The change in scan uniformity with the inclusion of an epoxy to hold the fiber to the PZT scanner. Scale bars correspond to 100 μm .

Fig. 7.

Several frames selected from Video 2 (MOV, 5.64 MB [URL: <http://dx.doi.org/10.1117/1.OE.55.1.013104.2>]). The effect of changing the phase in both north-south and east-west poles of the PZT in order to synchronize the scanners and produce a clear image. The scale bar corresponds to 100 μm .

Fig. 8.

Fig. 8 (a) Several frames selected from Video 3 (MOV, 6.22 MB [URL: <http://dx.doi.org/10.1117/1.OE.55.1.013104.3>]) as the resolution target is translated across the first PZT. (b) The full corresponding resolution target as a comparison.

Fig. 9.

(a) Several frames selected from Video 4 (MOV, 3.20 MB [URL: <http://dx.doi.org/10.1117/1.OE.55.1.013104.4>]) as the resolution target is translated across the first PZT with a larger scan range of 225 μm . (b) The full corresponding resolution target as a comparison.

Fig. 10.

(a) Several frames selected from Video 5 (MOV, 900 KB [URL: <http://dx.doi.org/10.1117/1.OE.55.1.013104.5>]) as the higher resolution features are translated across the first PZT with a scan range of 50 μm. (b) The full corresponding resolution target as a comparison.