Title: A compact mechanical probe for OCT based medical imaging that incorporates a MEMS scanner and a dynamically actuated objective lens

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Abstract: In this disclosure, we present the design of a compact hand-held probe for use in Optical Coherence Tomography (OCT) based biomedical imaging. There are two salient features that distinguish this instrument from it predecessors. To enable raster imaging, the beam that is directed at the sample being imaged has to be scanned about two orthogonal axes. This is typically done by using a mechanical mirror assembly mounted at the back of the probe, thus making the instrument bulky and cumbersome to use. In our proposed design, this mechanical assembly has been replaced by a two-axis MEMS scanner that is fitted inside the probe, thereby making the entire scan and probe system very compact. The second novel aspect of the proposed design is that, the lens closest to the sample is mounted on a linear guide that can be actuated precisely while the beam is being scanned. This shifts the focus of the incident beam by a few microns inside the sample, and hence images of successive layers separated by a few microns can be obtained, all of which when put together allow for a 3-D reconstruction of the sample image.

1. Background and Problem Statement

Optical Coherence Tomography (OCT) is an imaging technique that is commonly used to obtain high-resolution cross-sectional images of microstructure in transparent as well as non-transparent biological tissue [1-3]. The OCT setup is similar to a Michelson's interferometer with a reference arm and a scanning arm (Fig.1). The beam incident on the sample is required to perform a raster action to image a layer of tissue beneath the sample surface. While a single axis scan can produce only cross-section images of the sample, successive two axis raster scans can produce 3-D images. Some images produced using OCT are presented in Fig.2.

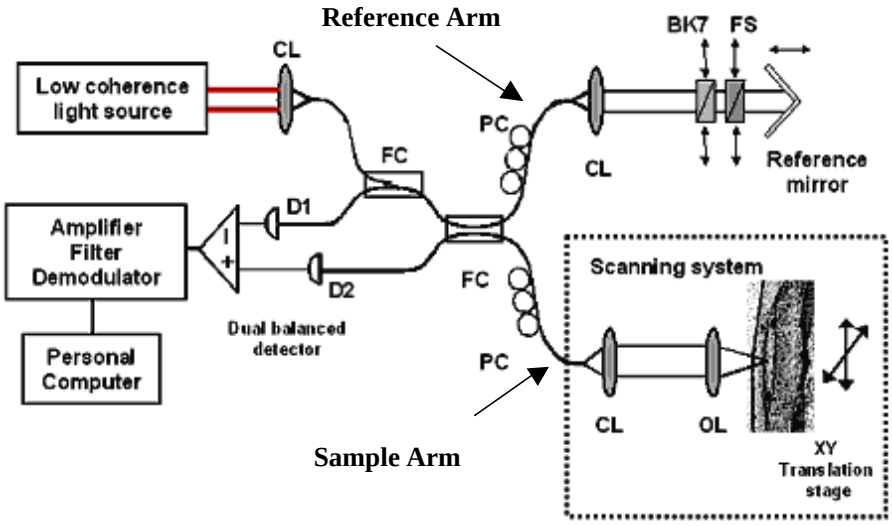


Fig. 1 Optical Coherence Tomography [1]

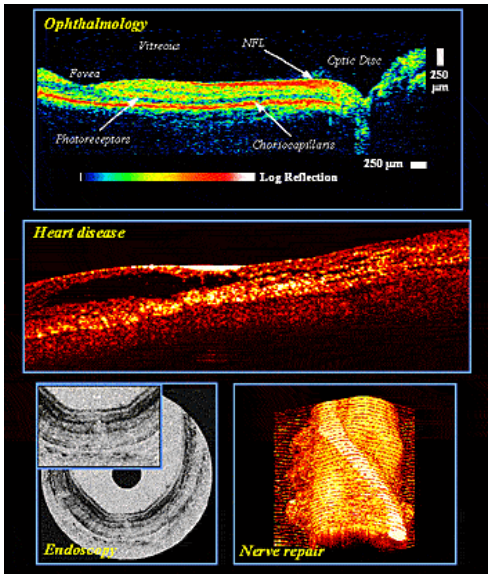


Fig. 2 Tomograms recorded using OCT imaging [4]

To achieve such raster action, a scanner is incorporated in the sample arm of interferometer. A schematic of the probe which houses the sample arm optics is presented in Fig. 3. Currently, this hand-held probe is used for medical imaging. Clearly, the scanner unit attached to the rear end of the probe makes it quite bulky and therefore cumbersome to use. In this disclosure we present a design that uses a MEMS scanner that is incorporated within the probe itself making the overall design very compact.

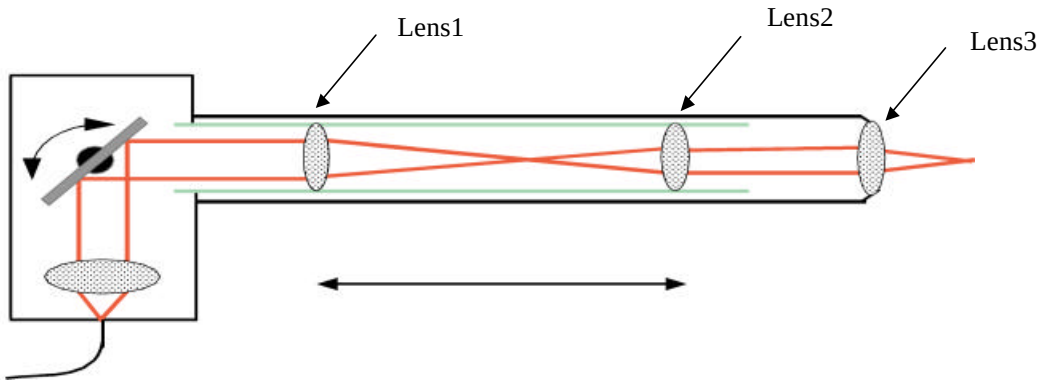


Fig. 3 Schematic of the current probe and scanning system used for OCT imaging

2. Proposed Design

As mentioned in the previous section, the mechanical scanning mirror assembly is replaced by a 2-axis MEMS scanner. A brief description of this MEMS device is presented here. The reader is referred to the MIT Technology Licensing Office Case titled "Two-axis Optical MEMS Scanner" by Awtar et al.

The two-axis optical MEMS scanner design is based on a novel resonant structure that provides optimal raster scanning action. The two scanning axes are orthogonal and are designed to be highly decoupled. Furthermore, translational errors of the mirror are eliminated by using the principle of virtual pivot for cantilever beams. PZT electrodes are employed to excite the structure at the frequencies that correspond to its two desired natural vibration modes. Based on preliminary analysis, the following device specifications have been predicted for the scanner:

Mirror dimension: 1 mm x 1 mm
Overall device size: 5mm x 5mm
Scan frequencies: 550 Hz and 15.5 kHz
Scan angle (mechanical): +/- 10 º
Power Consumption: < 1mA at 20V

To incorporate this MEMS device within the probe, it is packaged in a molded plastic "seat", also shown in Fig 4. The chip is epoxied into an inset region in the seat and is self-aligned against the edges. A second inset in the seat, allows for large deflections of the mass during bending without impacting the package.

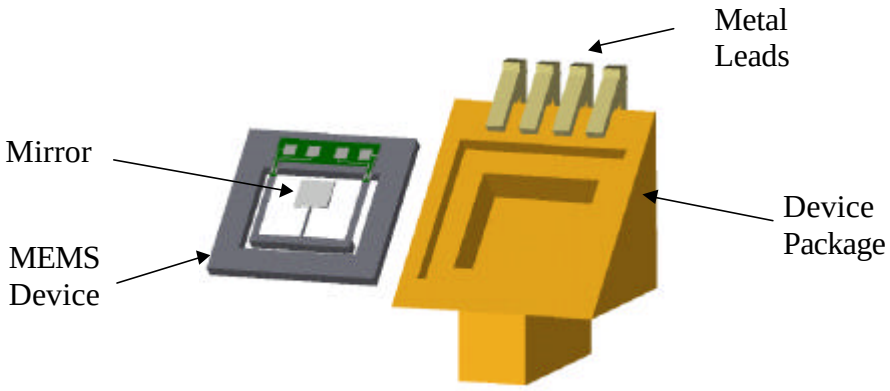


Figure 4. Device and package separated to show insets in package.

The seat includes metal leads to which the external electronics are connected. Contact pads on the device are wire-bonded to these metal leads, as shown in Fig 5. A small amount of gel can be placed over the wire bonds to provide insulation.

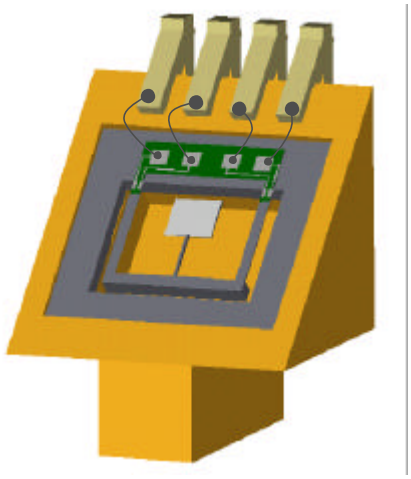


Figure 5. Device epoxied into the package

One embodiment of the entire probe with the above mentioned MEMS scanner is presented in Figure 6. The probe assembly consists of four basic modules: the front cap, the main tube, the scanner housing, and the rear cap. These are assembled with their components, and then screwed together. Each of these modules is individually described in the following paragraphs and the overall assembly is also discussed.

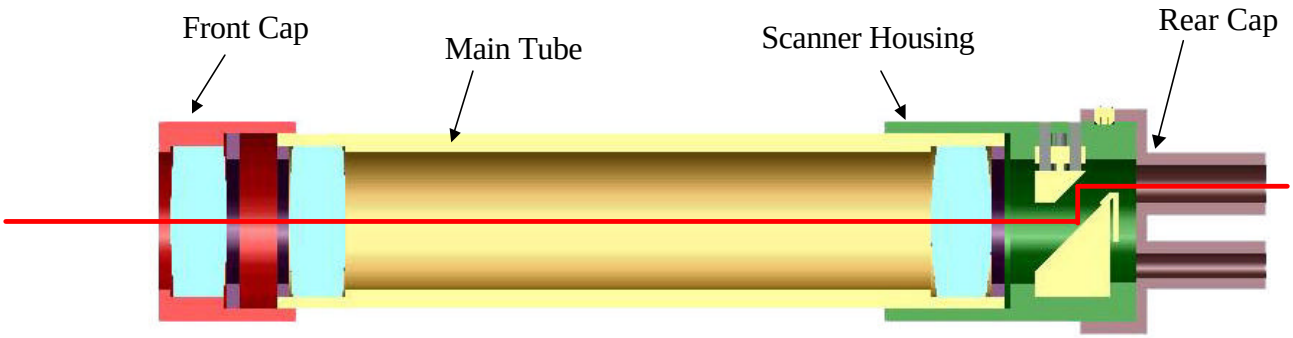


Figure 6. Cross-Section of the Probe

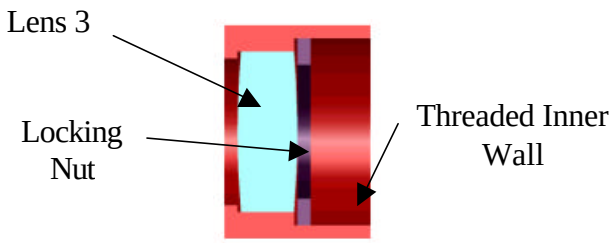


Figure 7. Front Cap

The front cap includes the lens closest to the sample, Lens 3, held in place by a locking nut. The inner wall of the front is threaded to accommodate the locking nut and allow assembly with the main tube, which screws inside the right end of the cap.

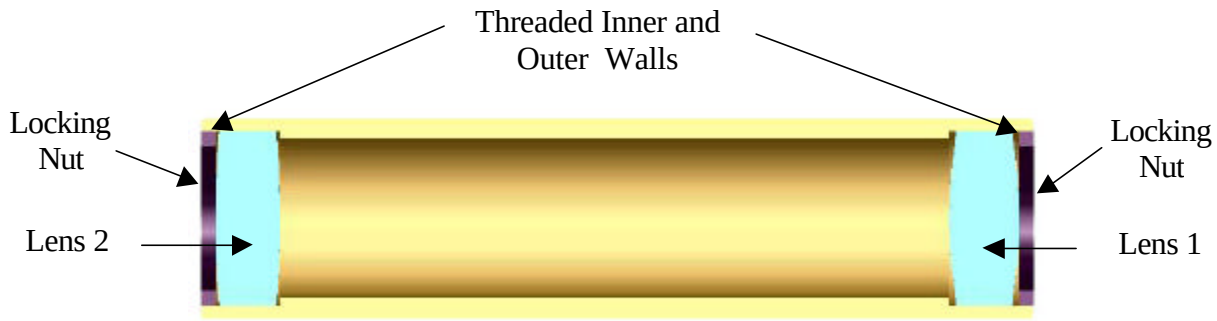


Figure 8. Main Tube

The main tube holds the other two lenses, Lens1 and Lens 2, each held in place by a locking nut. Both ends of this tube are threaded on the inside and outside faces, to accommodate the locking nuts, and allow for assembly to the front cap on the left, and the mirror housing on the right.

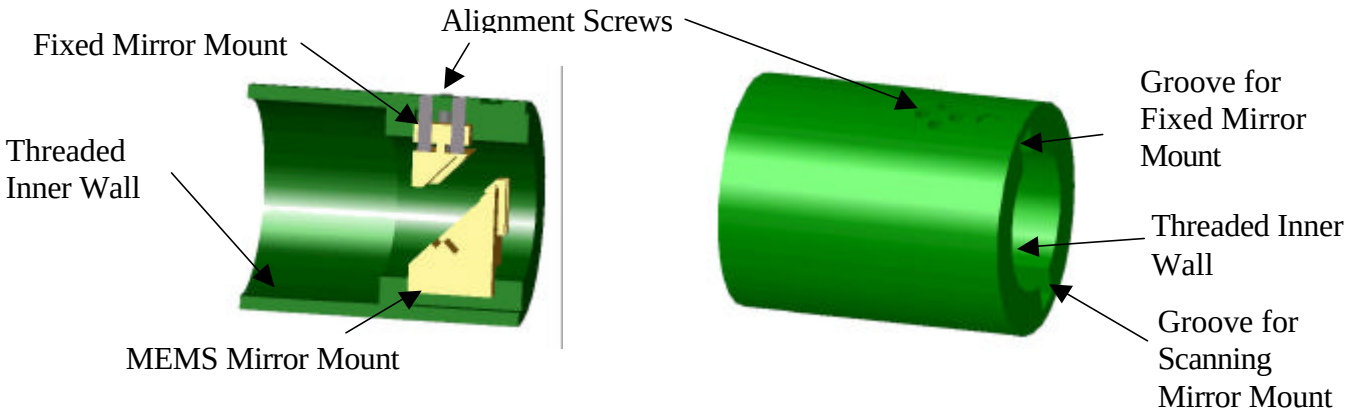


Figure 9. Mirror Housing

Fig 9 shows a cross-section view and an external view of the mirror housing. On the left side in the above cross-section view, the mirror housing is threaded on the inner face to accommodate assembly with the main tube. On the right, it is bored to a smaller diameter and two diametrically opposite grooves are provided for guiding the mirror mounts or seats.

Two mirror mounts, shown in Fig 10, are slid into these grooves. The upper mount holds a fixed mirror, and the lower mount holds the MEMS scanner. Both mounts hold the mirrors at 45° to the horizontal, and the mirror faces are therefore parallel. The male features on both mounts serve to install the mounts into the mirror housing. Once slid into place these two mounts are epoxied in their respective positions. This arrangement of mirrors is used because the laser beam enters the probe rear at an off-centered position, while the beam leaving the scanner mirror needs to be concentric with the probe and the lenses. This is well illustrated in Fig 6 by tracing a beam path as the laser beam enters and exits the probe (red line).

The fixed mirror mount is attached to the male part that slides along the upper groove in the mirror housing, by means of an hour-glass flexure. This feature allows for alignment of the fixed mirror. The four alignment screws above the fixed mirror mount may be extended or retracted to adjust the angle of the fixed mirror to a very fine degree. This is an important aspect of the design because it allows the overall assembly to accommodate manufacturing tolerances. In the absence of these alignment features, it would be very difficult to ensure that the incoming beam hits the scanner mirror exactly at its center.

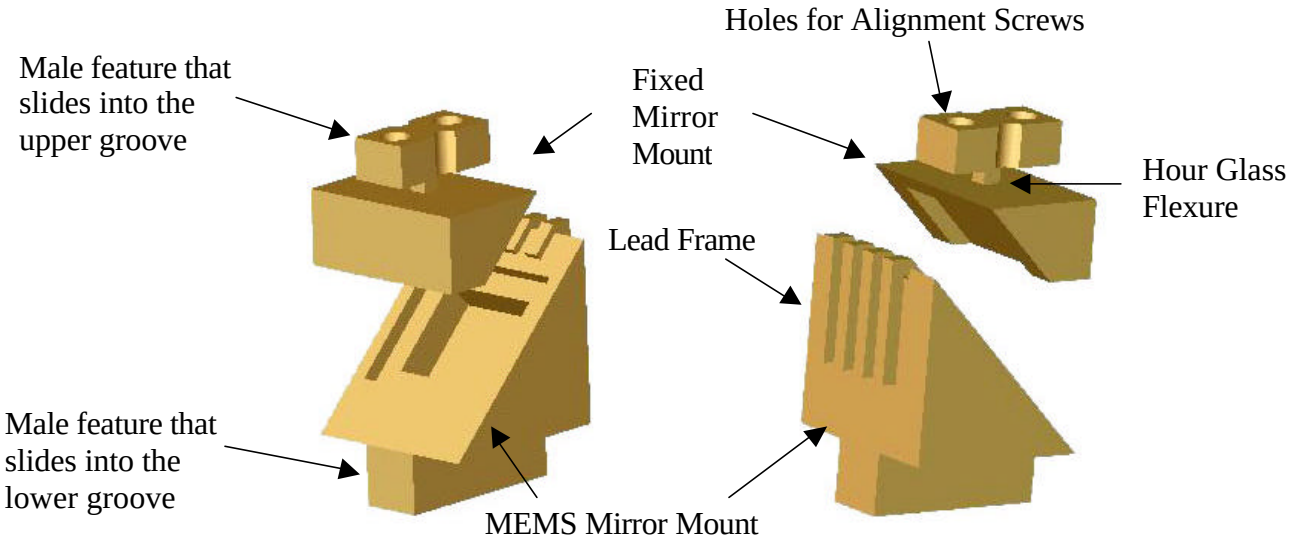


Figure 10. Two views of the Mirror Mounts

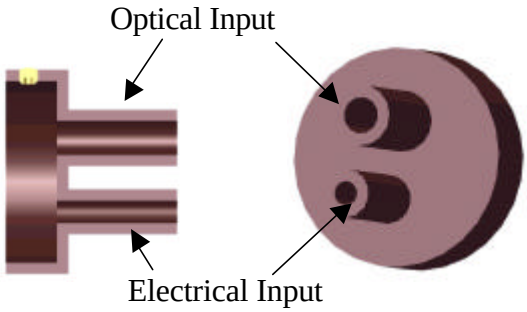


Figure 11. Rear Cap

The rear cap covers the mirror housing from behind and holds the fiber optic cable and signal cable going to the probe. This rear cap can be made out of a rubbery plastic so that it easily slides on mirror housing and is snugly held in place.

A fully assembled probe is illustrated in Figure 12, and is very similar to a standard white board marker in size and appearance. In comparison to the existing design of Fig. 3, this is a much more compact and hence convenient to use instrument.

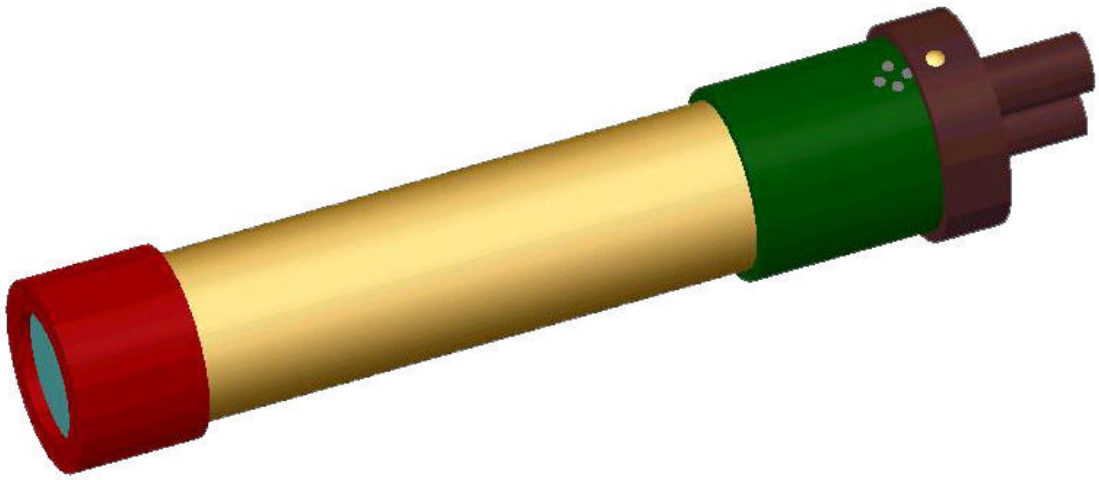


Figure 12. Fully assembled probe

Note that in this embodiment, once the probe is assembled, the Lens 3 remains static. A second embodiment is proposed in which Lens 3 is mounted on a precise axial bearing based on a linear bearing design disclosed in MIT TLO Case No. 09561, "Parasitic Error-free Symmetric Diaphragm Flexure, and a set of precision compliant mechanisms based it: Three and Five DOF flexible torque couplings, Five DOF motion stage, single DOF linear/axial bearing", by Slocum and Awtar. As indicated earlier, in this embodiment it shall be possible to obtain 3-D images of the sample being scanned in real-time.

Component specifications like lens sizes and locations can be obtained by performing a simple optics analysis for a given set imaging requirements, e.g., desired spot size of the laser beam on the sample and location of the beam focus beyond the final lens (Lens 3). For a particular case, this analysis is presented in the reference [5]. This may be repeated for a different set of imaging requirements.

References

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