A MEMS BASED OPTICAL COHERENCE TOMOGRAPHY IMAGING SYSTEM AND OPTICAL BIOPSY PROBES FOR REAL-TIME, HIGH RESOLUTION *IN-VIVO* AND *IN-VITRO* 2-D OR 3-D IMAGING

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A fully-functional, real-time optical coherence tomography (OCT) system based on a high-speed, gimbal-less micromachined scanning mirror is presented. The designed MEMS control architecture allows the MEMS based imaging probes to be connected to a time-domain, a Fourier domain or a spectral domain OCT system. Furthermore, a variety of probes optimized for specific laboratory or clinical applications including various minimally invasive endoscopic, handheld or lab-bench mounted probes may be switched between effortlessly and important driving parameters adjusted in real-time. In addition, artifact free imaging speeds of 33µs per voxel have been achieved while imaging a 1.4mm×1.4mm×1.4mm region with 5µm×5µm×5µm sampling resolution (SD-OCT system.)

In this work we present our latest "optical biopsy" system realized via MEMS based optical coherence tomography imaging. We also present a variety of MEMS probes, which have each been designed for a specific application area. By combining the unique advantages of time-domain, Fourier domain or spectral domain OCT systems with the properly optimized MEMS probe we are able to achieve truly optimal results for specific applications. In some cases it is desirable to achieve maximum optical resolution; in others higher acquisition rates or larger fields of view may be desired. Many parameters of the MEMS device and the optical probe must be selected at the time of design, fabrication or assembly (such as the NA of lenses, number of lenses, size of the silicon die and the diameter of the scanning aperture.) Other parameters may be adjusted on a case-by-case basis before an imaging session, such as the spacing of lenses. However, these are all time consuming operations which require recalibration of the imaging probe. On the other hand using the custom MEMS controller it is possible to adjust many drive parameters and make decisions regarding certain trade-offs in real-time. Therefore, the clinician can select the best probe for a specific application and still make some choices requiring field of view, image resolution band acquisition speed continuously during an imaging session.

Optical coherence tomography is an imaging modality capable of providing high resolution cross-sectional images of tissue and other materials [1]. A schematic diagram of a simplified version of the 3D MEMS Time-Domain OCT system is provided in Figure 1. Light from a low coherence source (1310nm, bandwidth of 70nm) is coupled into a fiber-optic Michelson interferometer. A rapid-scanning optical delay (RSOD) in the reference arm provides a variable optical path length utilizing a grating to separately control the phase and group delays; in the sample arm the endoscopic MEMS scanning probe directs a focused laser onto the sample surface. The probe contains an optical system optimized for the specific imaging application; the MEMS device and the optics in the probe determine the lateral resolutions while the coherence length of the source determines the resolution in the depth direction.

The MEMS controller is an independent micro-processor controlled unit which interfaces to the OCT image acquisition system. The OCT hardware provides information regarding the scan setup and timing as well as a sampling sync pulse. Stored data describing the connected device is employed to determine proper filtering, phase delays, offsets etc. based on the requested scan pattern. The signals are generated by two on-board DSPs. Following the amplification stages (150V maximum output) protection circuitry is incorporated to insure patient safety. An important note is that during normal imaging the micro-mirror is driven in a point-to-point manner, such that when the fringe-pattern sampling is performed the mirror is stationary thereby eliminating motion artifacts. Also, the software may compensate for lens distortions or easily compute a map to scan a flat surface rather than an arc *et cetera*.

The MEMS scanning actuators are monolithic, single crystal silicon (SCS), 2-dimensional, gimbal-less, vertical comb-driven structures. The devices are designed and realized in a self-aligned DRIE fabrication process on SOI [2, 3]; the die for endoscopic packages has an area footprint of 2.6mm×3.3mm. The mirrors are fabricated in a separate SOI process and later bonded to the actuator. This design approach allows the mirror and the actuator to be independently optimized, in addition, the MEMS and optical designers have a much broader design space when making trade-offs between mirror size and speed. The apertures are metalized, low-inertia, SCS structures with a thinned mirror plate (2-5µm), thick stiffening trusses (~20µm) and a tall standoff pedestal (~120µm). A variety of scanners with 800µm, 1mm, 1.2mm, 1.6mm and 2.0mm mirror diameters have been realized. Images of scanners with bonded mirrors are presented in Fig. 1. In Fig. 2 sample FD-OCT images are shown while Fig. 3 presents images from the TD-OCT, SD-ODT and SD-OCT systems.

Numerous *in-vivo* and *in-vitro* images have been collected of healthy and diseased tissue. We have also employed the system in unguided imaging of hamster cheek poach tissue, where sub 500µm regions of dysplasia have been identified in real-time (and later verified via histology) by experts in the field. It is believed that the "optical biopsy" capability provided by the minimally invasive endoscopic probes as well as hand-held and laboratory imaging probes developed from this work will continue to have a more and more significant impact on clinical treatment and medical research.

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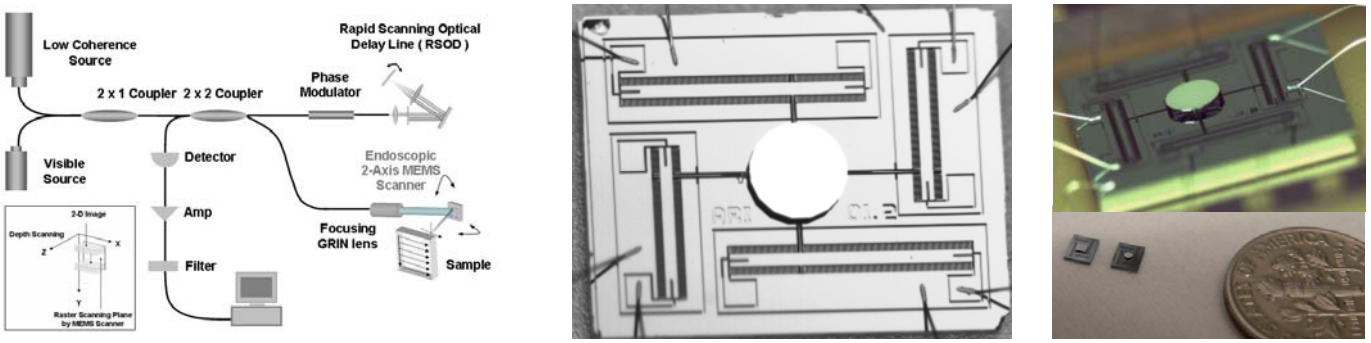

Figure 1. ***(left)*** *A simplified schematic diagram of the time-domain OCT system employing an endoscopic probe* ***(center)*** *A stereo microscope micrograph of a fully assembled, functional endoscopic scanner. The die is 2.8mm×3.3mm with a 1mm bonded mirror.* ***(right, top)*** *A stereo microscope micrograph of a larger actuator die with a 800μm mirror attached.* ***(right, bottom)*** *An image of two scanners with different mirror apertures ready to be bonded into an endoscopic package, a US dime is included for size reference.*

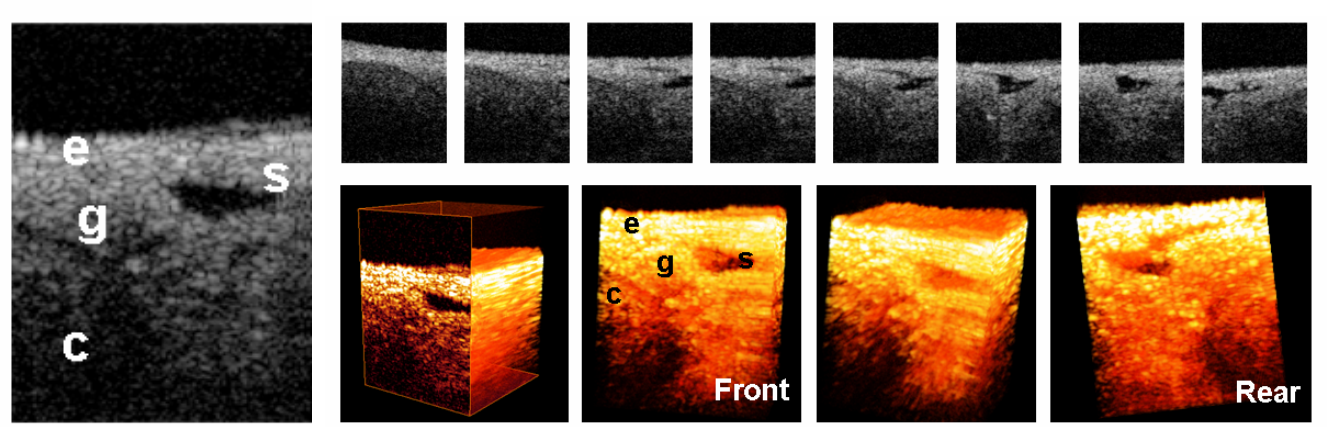

Figure 2. ***(left)*** *An image of healthy rabbit trachea from the Fourier domain OCT system showing the (e) epithelium, (s) sub-mucosa, (g) glands and (c) cartilage, the sampling resolution is 10μm×10μm×10μm and the volume imaged is 1.0mm×1.0mm×1.4mm (a single slice is shown.)* ***(right, top)*** *Sequential cross-sectional images taken around the diameter of the trachea of a healthy rabbit at a specific location.* ***(right, bottom)*** *3-D reconstructions of tissue from the same rabbit trachea.*

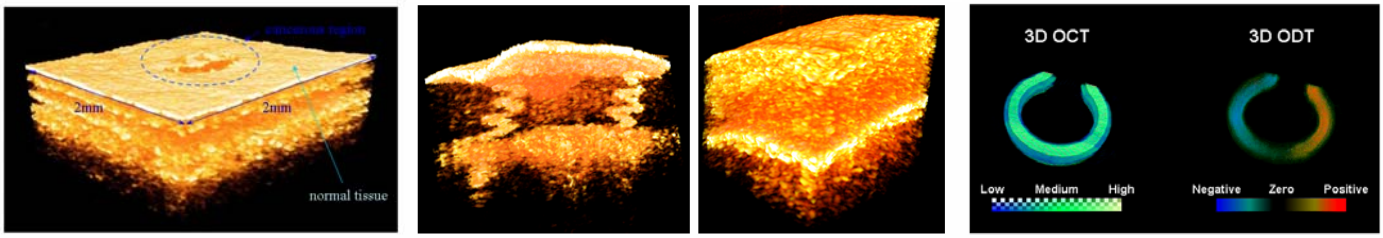

Figure 3. ***(left)*** *A 3-D reconstruction from our time domain OCT system of a section of hamster cheek poach containing a diseased region at the center; the imaged region is 2mm×2mm×1.4mm with a sampling resolution of 10μm×10μm×5μm.* ***(center, left)*** *An image of a human finger from the spectral domain OCT system with thresh-holding applied to clearly visualize the sweat-glands which have a diameter of approximately 20μm;* ***(center, right)*** *an image of a normal section of hamster cheek poach tissue. The sampling resolution is 5μm×5μm×5μm and the volume imaged is 1.0mm×1.0mm×1.4mm.* ***(right)*** *Structural (OCT) and flow (ODT) images of fluid-flow around a bend in a micro-channel.*

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Video of real-time image collection as well as 3-D renderings which may be manipulated in real-time and samples of various MEMS based probes will be made available at the conference.

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