Fully Distal Scanning Large Area 3D Endoscopic Optical Coherence Tomography

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ABSTRACT

As an alternative to random excisional biopsy, optical biopsy employing microelectromechnical systems (MEMS) based three-dimensional endoscopic optical coherence tomography (OCT) has been demonstrated. However, its limited scanning range leads to sampling errors. Therefore we present an approach for large area 3D imaging utilizing fully distal scanning configuration. A linear micromotor integrated within the distal end of a miniaturized catheter simultaneously performs rotational and translational scanning, which totally eliminates the requirement for external actuating devices for fiber twisting and stretching. 3D volumetric images of tissue samples can be obtained by helical scanning geometry.

INTRODUCTION

Optical coherence tomography (OCT) has become an emerging imaging technique that is capable of providing high resolution cross-sectional images of scattering tissues both *in vivo* and *in vitro* [1]. In recent years, swept-source based OCT systems [2] have been successfully developed featuring fast data acquisition rate up to several hundred thousands A-lines per second, which has demonstrated the capability of 2D or 3D volumetric imaging in real time. Endoscopic application of OCT and the concept of "optical biopsy" were firstly introduced nearly ten year ago [3] to avoid specimen damage caused by traditional invasive biopsy and histological methods for early diagnosis and identification of malignant cancer. The main challenge to implement OCT endoscopes is how to miniaturize the probe, fast steer the near infrared light beam for scanning and collecting reflected signals from tissue samples in high efficiency. MEMS based OCT probes integrated with post-objective distal scanning mechanism enabling high speed three dimensional imaging were developed recently. A variety of MEMS actuation mechanisms, such as electrothermal [4] and electrostatic [5] actuation, had been proven excellent reliability and low power consumption. Sampling errors leading to missed diagnoses are common with random biopsy, since the diseases may disseminate within a large tissue area and the biopsy operation only

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sample a small fraction of the tissue under investigation. Typically 3D volumetric data with dimension of 1mm x 1mm x 1mm can be obtained by using aforementioned MEMS based distal scanning OCT endoscopes, which still can not meet requirements for large area 3D scanning. A hybrid configuration of integrated MEMS micromotor and external translation stage based solution for this purpose has been reported recently [6] but the optical fiber still suffered to stretching forces induced by translational motion and hence lateral scanning speed is limited. This project aims to develop a fully distal scanning large area 3D endoscopic OCT for *in vivo* clinical imaging, which totally eliminates the requirement for external actuated devices for fiber twisting and stretching.

DESIGN AND IMPLEMENTATION

System description

Our design is based on a commercially available piezoelectric micromotor (SQL-1.5-6, New Scale Technologies, United States) with 1.55 mm x 1.55mm x 6mm tiny dimension and nanometer resolution, which is specially optimized for precision linear actuation. The linear micromotor consists of four piezoelectric plates bonded to a threaded metal tube, with a matching threaded screw, as shown in Fig. 1. A two-channel square wave is used to bend the piezoelectric plates to create an orbital “hula hoop” motion of the tube, causing the mating screw to rotate and translate. Reversing the phase shift reverses the direction of the orbit, and hence the direction of the screw. The highest efficiency of the mechanical coupling between the tube and the screw is achieved at the ultrasonic frequency matching the first bending resonant frequency of the tube, which is approximately 146 KHz. Core task of this project is to develop a driver circuit for the micromotor to provide two-channel wave signal with the resonant frequency of 146 KHz. A 2mm right angle microprism (FOCtek Photonics Inc, China) coated with protected silver high reflective thin film was mounted on the tip of the threaded screw to redirect weakly focused beam by 90^{o} into a sample. Two miniature transmissive optical interrupters (EE-SX 1107, Omron, Japan) were incorporated with the micromotor holder in order to limit the lateral moving range of the micromotor with in 3 mm.

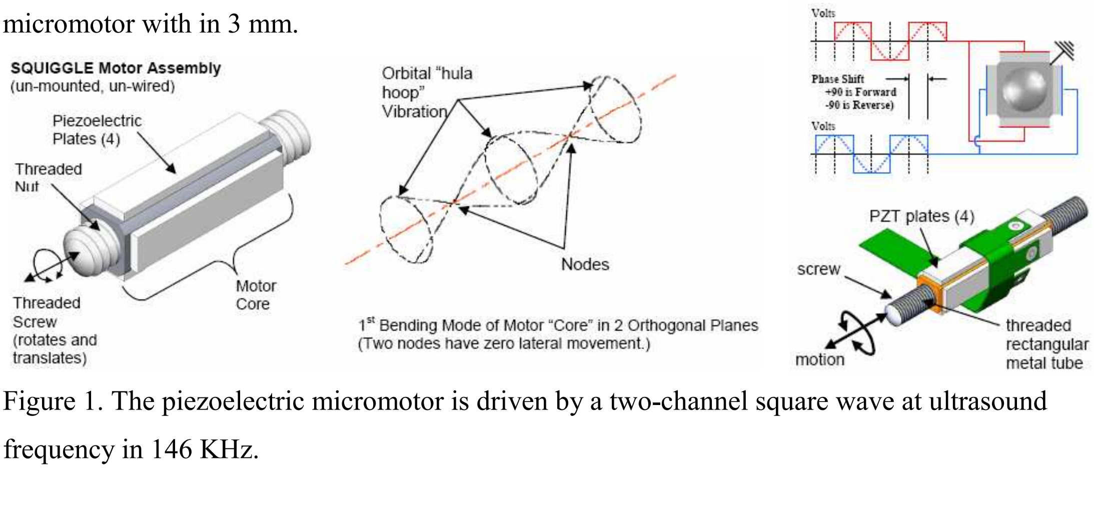

Figure 1. The piezoelectric micromotor is driven by a two-channel square wave at ultrasound frequency in 146 KHz.

To demonstrate its performance, the assembly of micromotor with microprism was connected with a high speed swept source OCT system (OCM1300SS, Thorlabs, United States). The schematic diagram of the system is shown in Fig. 2. Thorlabs' SS-OCT system incorporates a high-speed frequency swept external cavity laser (Thorlabs SL1325-P16), which has a 3dB spectral bandwidth (>100nm). The swept source has a built-in Mach-Zehnder Interferometer that provides the frequency clock for the laser. The main output of the laser is coupled into a fiber-based Michelson interferometer and split into the reference and sample arms using a broadband 50/50 coupler. In the reference arm of the interferometer, the light is reflected back into the fiber by a stationary mirror, and the reflectivity is controlled by a variable optical attenuator. Frequency clock signals internally generated by MZI were used to initialize and trigger data acquisition procedure of the DAQ card in the working station. In the sample arm, the light is fiber coupled into the microscope head and focused onto the sample surface by a long working distance objective. The sample is placed on a stage, providing XY and rotational translation. An integrated CCD camera in the microscope head provides a conventional microscopic view of the sample, which aids sample alignment. A-line acquisition trigger signal generated by the swept light source was fed to a 14 bit, 125 MS/s PCI digitizer (ATS460, AlazarTech, Canada) to initiate data acquisition for OCT interference fringe signals. A pair of XY galvo mirrors scans the beam across the sample surface, creating 1D, 2D, or 3D images.

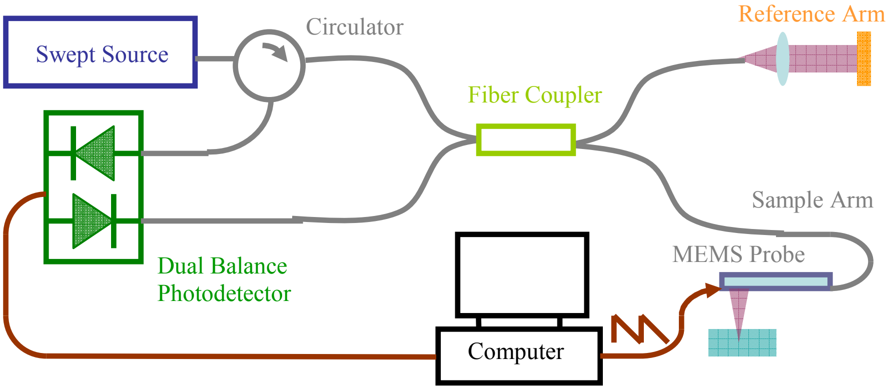

Figure 2. Schematic diagram of the swept source OCT system integrated with the two axes MEMS scanning probe.

Driver Circuit for Micromotor

As indicated, developing a driver circuit for driving the piezoelectric micromotor is main content of this project. The driver circuit should have the capability of providing two-channel square wave with 90^{o} phase shift and stable 146 KHz frequency and digital logic for motion control of the micromotor, including speed and direction of motion. Motion speed was controlled by varying the amplitude of the square wave and motion direction was determined by the phase order between two-channel signals. The schematic diagram of the driver circuit is shown in Fig. 3.

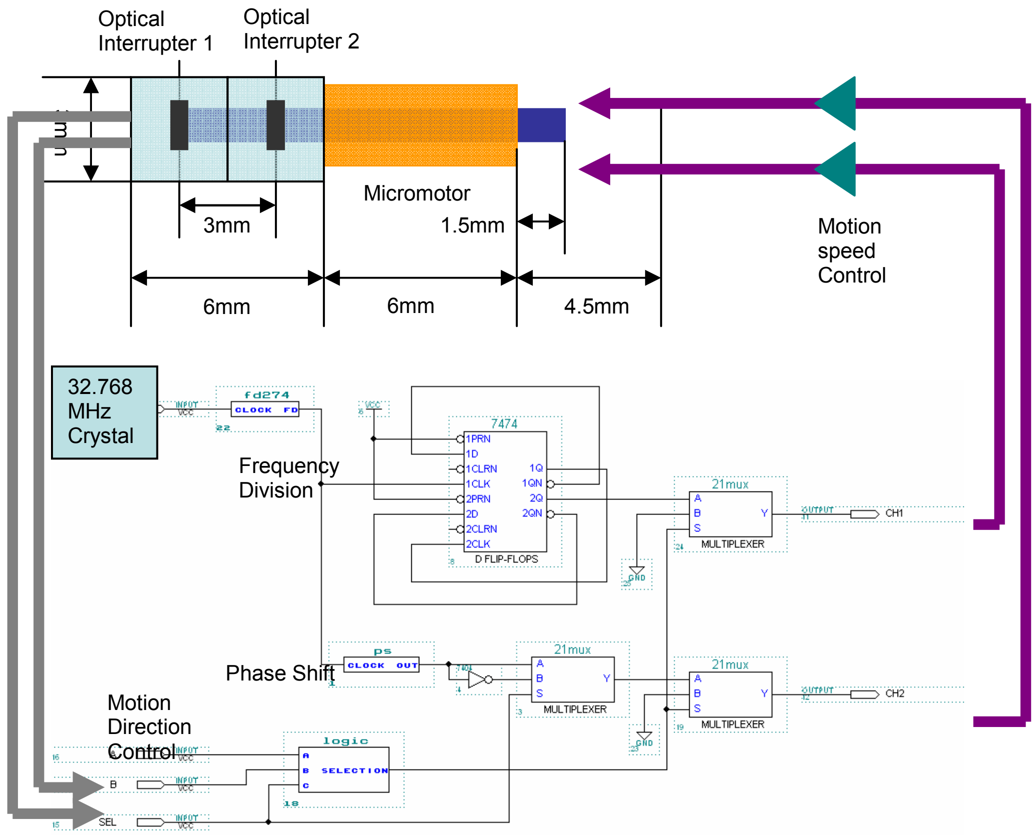

Figure 3. Schematic diagram of the driver circuit.

Due to high quality factor of piezoelectric plates, any deviations from the resonant frequency of the micromotor cause significant loss in mechanical coupling efficiency from the metal tube and the threaded screw, hence the loss in motion speed of the micromotor. So stable signal source was required to provide 146 KHz and the frequency shifting should be also minimized for linearly scanning. A 32.768MHz crystal oscillator was selected as base frequency source which generates all frequencies we required. Top level schematic of digital part of the driver circuit is shown in the central part of Fig. 3. Four terminals on the left side serve as inputs and defined as 32.768MHz base frequency source, feed back signals from optical interrupter A, B and manually forward/backward motion selection, respectively, from top to bottom. Two terminals, named as CH1 and CH2, are two channels square wave signals. Blocks in the top level schematic indicate some functional modules included and their implementations are shown in Fig. 4, 5 and 6. All digital components are implemented by an Altera EPM7064SLC complex programmable lodic device (CPLD) for convenience of debugging and design modification.

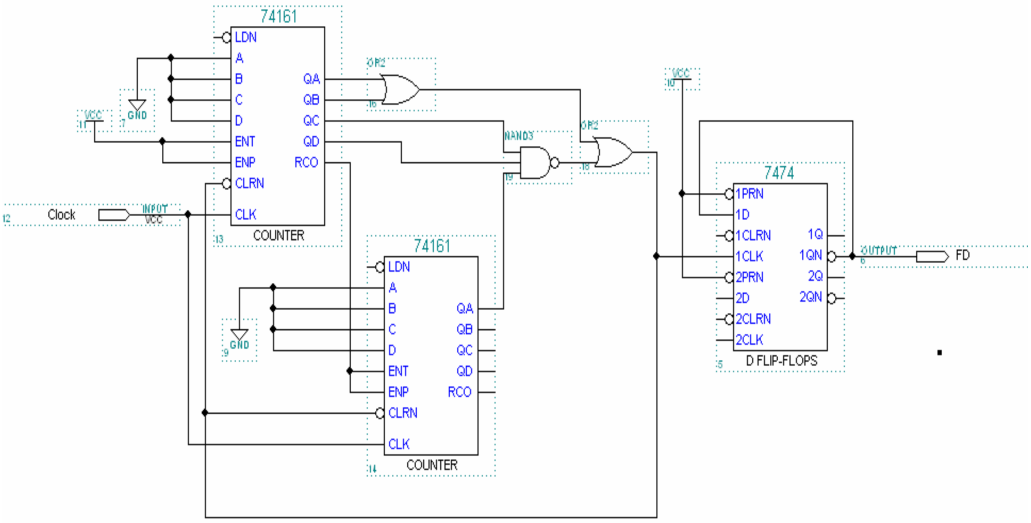

Figure 4. Frequency division by module "FD274".

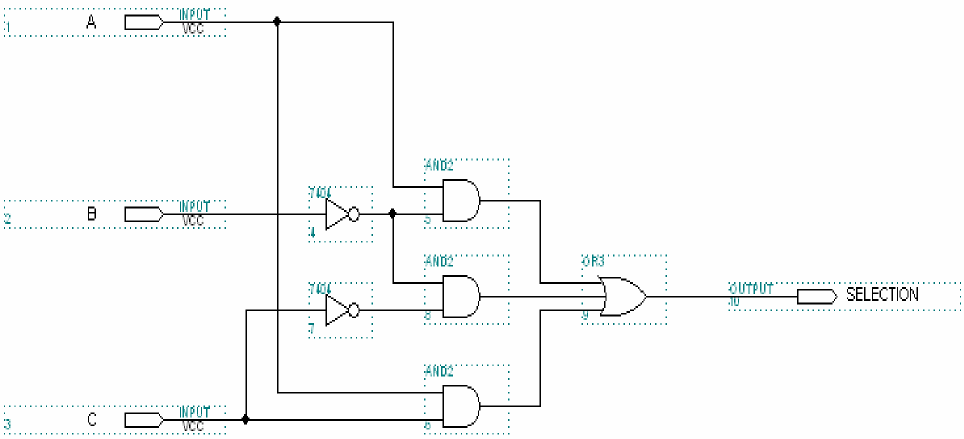

Figure 5. Module "logic" performs motion control of the micromotor in collaboration with two miniature optical interrupters.

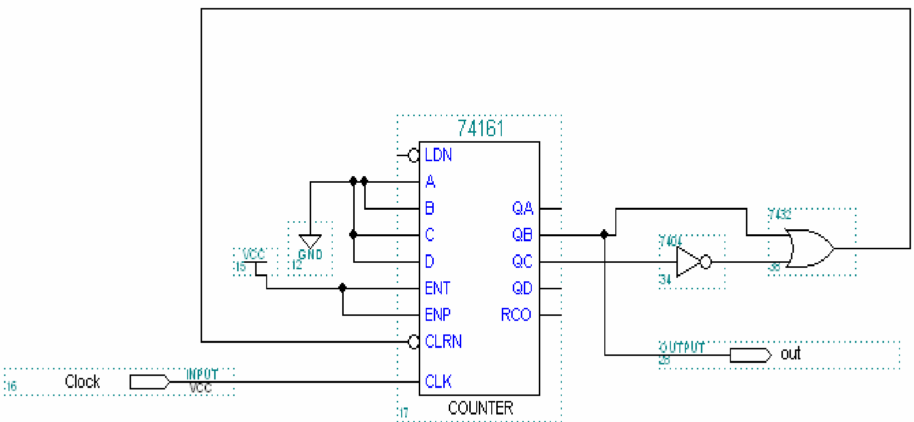

Figure 6. Module "PS" realizes 90 degree phase shifting for two channels driving signals.

Translational velocity of the micromotor was controlled by varying the amplitude of two-channel driving signals. Normally the amplitude is ranging from 20 volts to 40 volts for up to 10 mm/s running speed without load. Usually signal conditioning technique is based on a variety of analog circuits based on operational amplifiers (op amp), such as signal amplification. In spectral domain, square wave contains frequency components ranging from DC to infinite high hence it requires gain bandwidth product (GBP) of the op amp as high as possible. Both rising edge and falling edge of square wave signals after amplification should still keep steep so voltage slew rate of the selected op amp should also be as high as possible. The mircromotor needs about 10-30 mA working current which is provided by the signal amplification circuit. A non-inverting amplifier was built based on a single power supply operational amplifier (EL 2045, Intersil, United States) to increase the amplitude of the square waves from standard TTL 5 V to required 20-40 V. Fig. 7 and Fig. 8 shows square wave forms before and after amplification. Photos of fabricated circuit and the micromotor on a polymer platform are shown in Fig. 9.

Figure 7. Square wave forms before amplification.

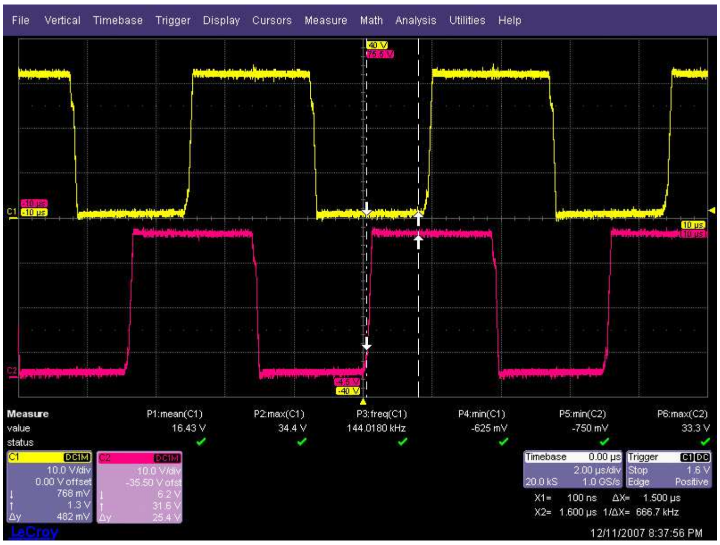

Figure 8. Square wave forms after amplification.

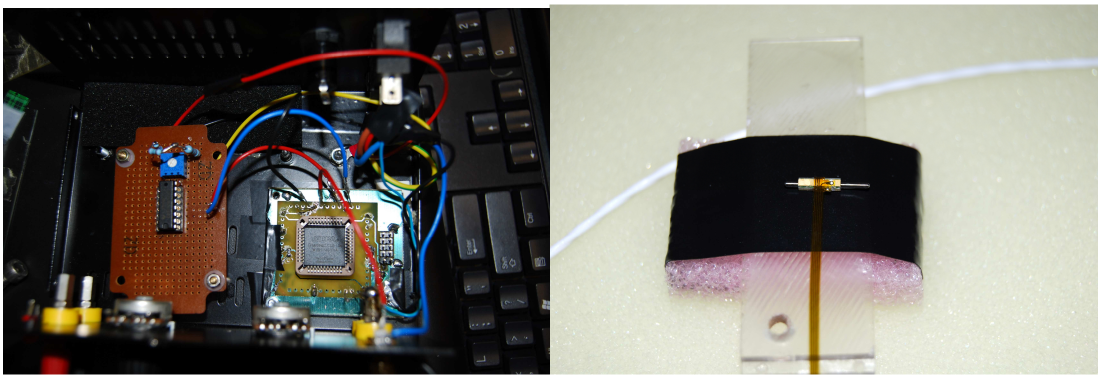

Figure 9. Fabricated driver circuit for micromotor (left) and micromotor on a polymer platform (right).

CONCLUSION

In summary, a new approach for large area 3D endoscopic imaging based on fully distal scanning mechanism has been proposed and a driver circuit has been fabricated to drive the piezoelectric micromotor. The next step is to integrate the micromotor, a small dimension right angle microprism and a GRIN lens into a biocompatible housing and connect the assembly to a high speed swept source OCT system for testing.

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