Optical Coherence Tomography Needle

Mid-Semester Report

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10/24/2007

ABSTRACT: A real time, in vivo method of imaging yielding high resolution images is needed. Previous solutions involving optical coherence tomography have incorporated moving parts, such as gears, which adds to the mechanical complexity of the design. Modifications this semester have focused on eliminating moving parts by using simple optical devices. The chosen solution relies on a transmission grating, an optical device that is based upon the principles of diffraction. Stepping increments with laser pulses allows the device to generate a 92 degree field of view. Future work will involve further maximizing the field of view by analyzing different options for transmission gratings (reflecting, immersion, etc) and encapsulating the needle to meet FDA regulations.

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PROBLEM STATEMENT

Our project involves creating a needle with imaging capabilities via optical coherence tomography (OCT). The needle has several optical components which include a fiber, lens and a diffraction optic. These components have several parameters that may be optimized. Following the compilation of these specifications, we will design the diffraction optic optimizing both the spatial and spectral resolution while considering the biological requirements.

BACKGROUND

Optical Coherence Tomography is a technology that was first pioneered in 1991, and has since become available and accepted as an effective imaging modality for many different applications (Huang et. al 1991). Applied to the human body, OCT can be utilized *in vivo* to image tissue structures during surgical procedures. An ideal OCT scan for producing significant image information would project to about 2 mm.

OCT provides a way to noninvasively obtain images which have a resolution comparable to that of optical microscopy. These images are obtained through a method which in many ways is analogous to ultrasound imaging; however it is conducted on a much smaller scale.

OCT functions on a concept called low coherence tomography. The basic premise of this technology is an ultra-short pulse of light is sent through a device called an interferometer. This splits the beam into two separate paths. One path, the reference beam, serves as a controlled wave pattern. The other beam, the sample beam, is sent to the imaging target. The sample beam interacts with tissue and scatters. Depending on the material properties, some of this scattered light will reflect back into the light source and ultimately back to the interferometer (Schmitt, 1999). Sophisticated processing power can then analyze how this reflected light compares to the reference beam (See Appendix B for a schematic). While the specifics of this processing are irrelevant to this design project, the end result is that one beam of light encodes a spatial transmittance of light relative to the distance from the imaging source (Huang, et. al, 1991).

The radial resolution of OCT is obtained through the interference of the sample and reference arms. The angular resolution can be obtained by many different methods. This is the key factor explored by this design project. The basic requirement of angular image encoding is having a quantifiable way of controlling where the beam of light is sent. Often, this is done by mechanically reflecting the light at different angles with a moving mirror or prism in a scanning

fashion (Fujimoto, 2000). However, there are other creative ways through which this angular encoding can be achieved.

MOTIVATION

Although OCT greatly surpasses the typical image resolution of ultrasound(4000μm), the penetration depth, or radial resolution, of OCT limits its practicality (Elliot, 1996). The depth limitation is typically around 1-2 mm, but is dependent upon the optical properties of the tissue. The depth is measured from the tip of the transducer to the points at which the scattering properties prevent light from reflecting back into the transducer to be processed. To undermine the penetration problem, the transducer may be incorporated into a small needle-like probe. Previous work has included larger catheter-based OCT transducers used to diagnose diseases in areas such as arteries and the lumen of the GI tract. Diseases diagnosed with these catheters include Barrett's disease, colon cancer, and arthrosclerosis (Tearney, et al., 1997, & Bouma et al., 2000). Additionally, smaller needle transducers (27 gauge) have been prototyped to be inserted into organs like the pancreas (Hwang, 2005). Similar to the other OCT probes, its function is to diagnose or track developments in diseases optically, without the need of biopsy.

DESIGN SPECIFICATIONS

After evaluating the limits of current technology and considering client expectations, the following design specifications were formulated. Both the needle and the catheter-based transducers rely on moving parts to create the image. To reduce the cost and increase the robustness of the design, eliminating moving parts is necessary. The size of the needle may be reduced if moving parts are not used. With the elimination of moving parts, the image changes from either a 360^0 washer like image or a conical image to a smaller planar pie-shaped image. The reduction of the image field of view is not a significant disadvantage. Regardless of the design concept, the image resolution obtained should be at least 20 um, which requires a 20 um beam of light. The outer diameter of the needle should be no more than 400 um. The design must meet these criteria while functioning on a wavelength range of 700 -1400 nm. This range is limited to the infrared portion of the electromagnetic spectrum because of the absorptive characteristics of water in tissues.

ALTERNATIVE SOLUTIONS

A wide range of designs were conceived. The range of optical tools used encompasses simple prisms and complicated fiber optics designs. In all the design alternatives, the chromatic deflector controls the sweeping arc (spatial resolution) as well as the spectral resolution.

COMMONALITIES AMONG ALTERNATIVE DESIGNS

The 20 um beam is transmitted through a fiber optic device. The light has already traveled through an interferometer. The reference arm of the interferometer remains stationary, while the sample arm moves (as the needle is moved around in the tissue). The light used will need to have a short coherence length, so as to match the path lengths; this way the reflectivity of a sample will be obtainable by moving the reference arm over a distance. The back-scattering of light from the tissue interacts with the mirror of the interferometer to create the image.

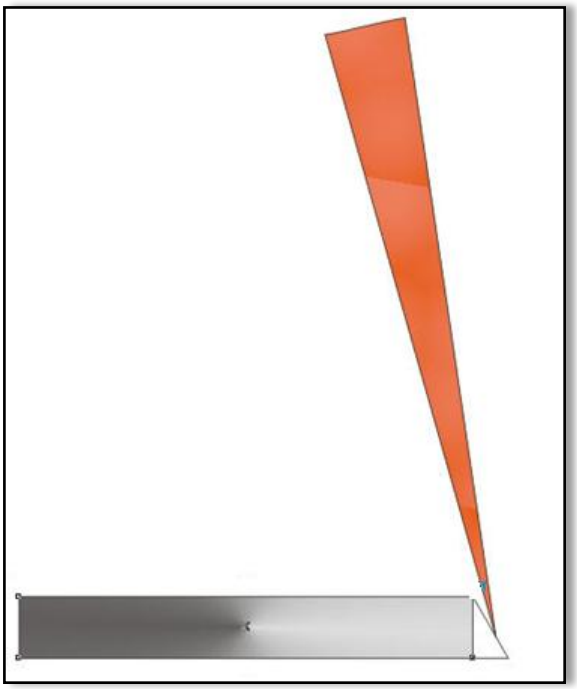

Figure 1: Prism (field of view 6.385 degrees); field of view is to scale. The rectangle represents the exterior of the needle and the triangular portion is the total field of view.

PRISM

Based upon the principle of refraction, a simple dispersive prism can perform the function of splitting light into its component wavelengths. Snell's Law dictates the angle of refraction, which is dependent on the refractive indices of the prism and the surrounding material. The index of refraction for tissue was assumed to be 1.333, similar to that of water. Preliminary computations as shown in Appendix C revealed that n_{prism} and height of the beam could be varied to obtain the maximum field of view (Figure 1).

SINGLE-MODE FIBER SYSTEM (FRONT-LOOKING) WITH CONVENTIONAL TRANSMISSION GRATING

The crux of this system is a transmission grating. Sending light through a transmission

grating directs the light to a specific location based on its wavelength. Increasing the number of grooves in the transmission grating elicits a broader field of view; satisfying the customer requirements for increased spectral resolution, an advantage not offered by the prism.

To increase spectral resolution, the number of grooves on the transmission grating needs to be maximized. Another possibility includes immersion gratings, which are made of materials possessing very high indices of refraction. This material is usually silicon, which elicits an index of refraction of approximately 4 (Professor Sheinis).

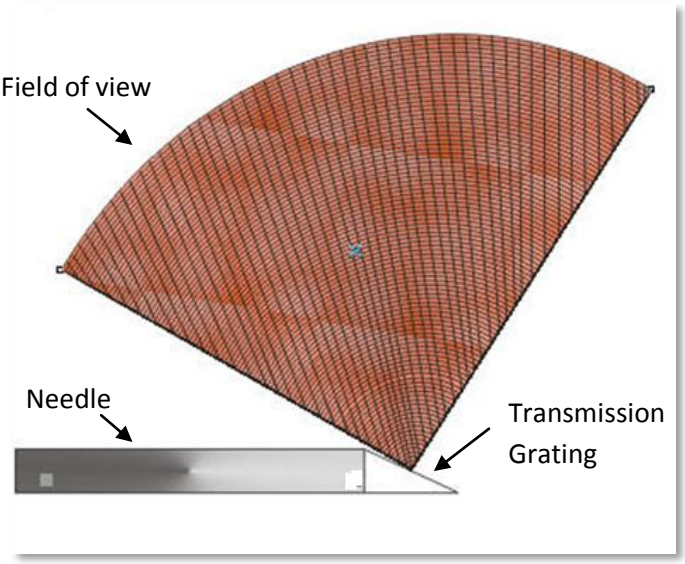

Figure 2: Transmission Grating (field of view to scale)
92^0 field of view. 46.6 um spatial resolution.

SIDE VIEWING MOVING PRISM

Competing design

Several designs of OCT needles have been developed and/or patented. One such competing design developed by a team at MIT consisted of a side-viewing OCT imaging needle incorporating distal beam-focusing prism optics. The model consisted of a single-mode optical fiber, a GRIN lens with a 250 um-diameter, and a 90 degree microprism. The distance between the optical fiber and GRIN lens is chosen such that the spot size, or waist diameter of the beam, and the focal distance is predetermined. The final unit was housed in a 27-guage hypodermic tube, which equates to approximately 406 microns. In order to obtain the image in a conical state, the researchers implemented a rotational device comprised of gears and a DC motor (Figure 3). The rotational mechanism was demonstrated to provide a 360 degree view of the image in a washer shape (Fujimoto, 2000).

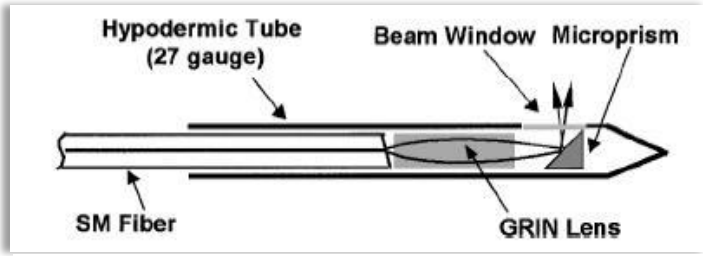

Figure 3: Moving Prism Design; Fujimoto, 2000; field of view is 360 degrees

ANALYSIS OF ALTERNATIVE DESIGNS

DESIGN MATRIX

A design matrix was compiled to determine which of the three designs should be pursued. The criteria were determined and weighted based on client input, product design specifications and background research. Since the needle's main function is to diagnose tissue abnormalities, image resolution and angular field of view were given the most weight. Costs of manufacturing, development, and administration are necessary economic considerations, but were given lower weights because the needle's utility far outweighs the monetary costs. Durability was given considerable weight because of concerns for patient safety. Needle diameter and versatility were given the least weight since they are not necessary for needle operation.

The prism optic scored high on economic considerations but poorly on image resolution. The prism with moving parts scored high on resolution and angular field of view. Its complexity, however, resulted in lower scores for other criteria. The transmission grating scored high on image resolution because of its diffraction capabilities. The lack of moving parts also gave it high scores for manufacturing cost and durability. The transmission grating design was thus chosen based on the design matrix (Table 1).

Table 1: Design Matrix

	Weights	**Transmission Grating Optic**	**Prism Optic**	**Prism w/ Moving Parts**
Angular field of view	0.20	7	3	10
Image resolution	0.20	7	2	8
Durability	0.20	7	7	4
Manufacturing Cost (per needle)	0.10	7	9	4
Cost of development	0.10	7	9	2
Cost to Administer	0.10	8	8	5
Needle Diameter	0.05	7	7	6
Versatility (side viewing vs. front viewing)	0.05	7	6	8
Total	**10**	**7.1**	**5.65**	**6.2**

LIMITATIONS/ADVANTAGES

PRISM

Attempts to improve the prism field of view would involve maximizing the index of refraction. However, this is limited by materials available. The highest index of refraction possible is 4.0, corresponding to silicon. The field of view does not improve significantly, even with this material.

COMPETITION: SIDE VIEWING MOVING PRISM

One major disadvantage was the presence of moving parts, specifically the gears and actuators. Moving parts would complicate the design significantly, especially because the size of the device is on the order of micrometers. The rotating mechanical components would also elicit a greater risk of mechanical failure, which could jeopardize the patient's safety. Additionally, the versatility of the design would diminish in regards to the ability to controlling development, manufacturing or administration costs.

The main advantage of this design was that it demonstrated an angular field of view of 90 degrees. This field of view could potentially be extended to 360 degrees due to the complete rotation of the needle by the gears and actuators of the design. Additionally, this design achieved a spatial resolution of 6.7 um, which was in agreement with the desired spatial resolution of 20 um.

SINGLE-MODE FIBER WITH CONVENTIONAL TRANSMISSION GRATING

A major limitation of this design is the restriction on the size of the beam that will be transmitted through the grooves. Since spectral resolution needs to maximized, the beam size would have to be increased so as to direct the light as mentioned previously. However, since the beam size is required to be 20 um, as per client specifications, the larger beam would have to be refocused (the initial sizing of the beam would be facilitated by the proper placement of a GRIN lens). The resizing of the beam complicates the design of the optical components; additional lenses would be required to perform refocusing.

Side-looking OCT needles have been designed before; though they have included moving parts, such as a gear, to increase the field of view by rotating the transmission grating (Fujimoto, 2000). The proposed design does not have any moving parts, which is a major improvement since it reduces the mechanical complexity of the design.

ETHICAL CONSIDERATIONS

Since the OCT needle will be used on human patients, it will need to be safe for use and approved by the FDA. All of the optical components that can possibly shatter inside the body will therefore have to be encapsulated, or coated, in a metal substance (this includes any possible lenses and chromatic deflectors). The size of the needle must be minimized so it is less invasive. In addition, the needle must be sterile before use. The needle will only be used once and then appropriately discarded.

FUTURE WORK

Based on the analysis of the weighted criteria, the transmission grating will be the diffraction optic of choice. Future development will focus on analysis of specific types of gratings, for example transmission vs. reflection gratings. Reflection gratings are effective for side-looking arrangements. In either case, maximizing the number of grooves the beam encounters will maximize the angular resolution. Possible areas of investigation include immersion gratings which prompt more bending of light as it exits the grating. In addition, for safety reasons, the needle must be encapsulated; metals are the ideal material for this. Methods for performing the encapsulation will need to be investigated.

CONCLUSIONS

A needle with optical coherence tomography capabilities is to be designed. The key component of this stage of design is control of spatial resolution of the imaging device. Several options were evaluated to achieve a scanning image to obtain this resolution. The three main methods considered were a prism, a diffraction grating, and a design based on a spinning needle. Since one of the main motivations of this design is to reduce costs and complexity, the moving parts design was eliminated. Then, the diffraction grating was determined to be the most promising design concept to meet the goals defined by the client. Future development of this product will focus on maximizing effectiveness of the diffraction grating, and exploring optical arrangements to allow for the most applicable and practical needle design.

ACKNOWLEDGEMENTS

We would like to thank Professors Block, Sanders and Sheinis for their advice.

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Appendix A

Product Design Specification

Needle OCT
Group Members:
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Karissa Thoma (Leader)
Peter Kleinschmidt (Communicator)
Vidhya Raju (BWIG)
Susie Samreth (BSAC)

Function:

Our project involves creating a needle with imaging capabilities via optical coherence tomography (OCT). The needle has several optical components which include a fiber lens and a diffraction optic. These components have several parameters that may be optimized. Because of the complex nature of the project, our focus is to design a diffraction optic with optimal imaging capabilities. Parameters we will consider include spatial and spectral resolution, as well as biological requirements.

Client requirements:

- Maximum diameter of needle 500µm.
- No loss of information because of encoding overlap. Wavelengths cannot overlap in same order, or in separate intensity orders.
- Prefer no moving parts, illustrates need for diffraction optics.
- Image field made up of micro and macro-sweeps. Macro-sweeps result from optical coherence tomography imaging techniques. Micro-sweeps result from diffraction optic.
- At least 20 µm spatial and spectral resolution.

Design Requirements:

1. **Physical and Operational Characteristics.**

a) Performance requirements:

Needle must be mechanically robust since it will be implemented in various biological tissues. The needle must be strong and flexible to allow optimum penetration into the tissue, with a depth resolution of 20 um. The needle will be used only once before being discarded.

b) Safety:

The optics composing the needle may be composed of glass rods with a maximum diameter of 500 µm. Given the mechanical instability of these thin glass rods, a coating substance must be applied to further strengthen the optical probe. In the case that the glass rod breaks, the coating must contain all the glass, protecting the tissue from infection. The needle design should allow standard sterilization procedure before use. Additionally, the external surface of the needle should not induce an immune response.

Appendix A

c) Accuracy and Reliability:

Optical components involved must ensure the repeatability of obtaining images.

d) Life in Service:

A single needle must be able to function for an entire imaging session.

e) Shelf Life:

Assuming needle is in sterile packaging, the needle has an indefinite shelf life.

f) Operating Environment:

During use the needle must withstand biological tissue temperature (98.6^0F), pH 5.5 to 7.45. The needle will be stored in ambient temperatures.

g) Ergonomics:

The needle should be user-friendly and simple to operate.

h) Size:

The optical needle must have an outer diameter of 200 µm or less. A single needle can be used in one of the following applications: research, clinical, and surgical.

i)Materials:

The needle must be composed of substances acceptable for use in biological tissues by the FDA.

k)Aesthetics, Appearance, and Finish:

The external coating must be smooth.

1. **Production Characteristics**
    - **a) Quantity:**
        A single diffraction optic should be constructed for this semester.
    - **b). Target Product Cost:**
        When commercialized, $10; for design purposes, $100
2. **Miscellaneous**
    - **a). Standards and Specifications:**
        FDA approval necessary.
    - **b). Customer:**
        The concept of no moving parts and a live front view image.
    - **c). Patient Related Concerns:**
        The packaging of the needle must have approved sterilization requirements. The fiber carrying the wavelength encoded information from the needle to the processing area must a separate network so patient imaging information is hacked into. Each needle must be discarded after every use.

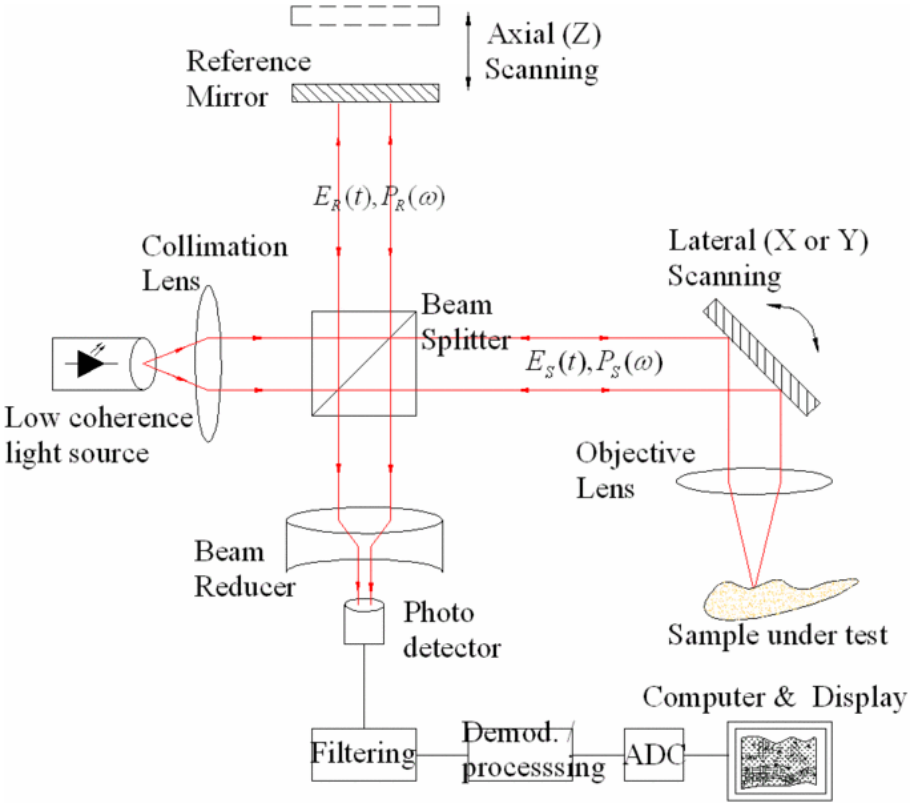
Appendix A

d). Competition:

Optical coherence needle patent number 6564087 has moving parts forms a washer image from side viewing port.

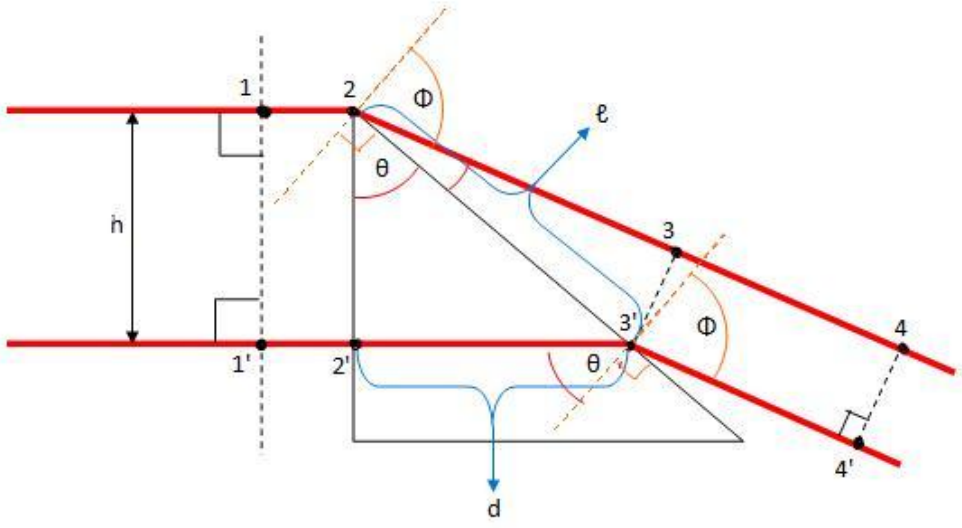
Forward Scanning Imaging Optical Probe, patent number US 7,261,687 B2, front viewing probe which uses two moving prisms.

Appendix B – Optical Coherence Tomography Schematic



Based on an image from: http://bil.nb.uiuc.edu/biophotonics/technology/oct

Appendix C – Prism Geometry



Created by Tuan Tran. Based on Information provided by Professor Scott Sanders.