Constructing a Model of the Cochlea from OCT Images

Group 2

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Abstract—*Cochlear Implant insertion is a surgical procedure during which an implant is placed into the cochlea of a patient with hearing loss. The implant augments the functionality of the cochlea, transmitting electrical signals that the patient's brain interprets as sound. We propose a robot-assisted approach that will improve upon standard practice for this surgery. This system guides the insertion of an implant using virtual fixtures enacted based on OCT imaging of the cochlea.*

Technical Summary

I. BACKGROUND

A. *Hearing Loss*

When sound waves enter the cochlea, they cause small hairs that line the cochlear interior to vibrate. These vibrations, when transmitted to the brain, are interpreted as sound. If these hairs are damaged, hearing loss may result.

B. *Cochlear Implant Insertion*

In many cases of hearing loss, especially those involving damage to the cochlea, hearing can be partially restored by way of a cochlear implant. This device incorporates an array of electrodes that curls inside the cochlea and transmits sound from an external receiver to the brain in the form of electrical signals. The insertion of the electrode array is a difficult procedure even for highly trained surgeons due to low visibility, the precision required, and the small scale of the force that can cause damage to the cochlea.

In order to access the cochlea, the surgeon must first perform a mastoidectomy and cochleostomy. The mastoidectomy machines the flesh (mastoid cells) around the cochlea, and the cochleostomy drills a hole into the temporal bone. Once this is complete the round window, the most direct entrance to the cochlea, is accessible. The surgeon then inserts the implant until a desired location is reached by the tip of the implant. This is typically just before the basal turn, which is the first turn in the spiral of the cochlea. This position is communicated by way of a marker on the implant itself. Once this marker reaches the site of the cochleostomy, the implant should be at the proper depth. The surgeon then grips the stylet, a wire that keeps the implant straight, and continues to push the electrode array. Because the electrode array is naturally curved, removing it from the stylet causes it to curve into the spiral of the cochlea and the insertion is then complete.

C. *OCT Imaging*

OCT imaging is based on the interferometry principle of light. This principle states that beams of light that are split, travel along different paths, and then recombine have a phase difference which can be analyzed to determine the difference in distance travelled by each beam [4]. In this case (see Figure 1) it means that our OCT system uses the phase difference of the two beams to determine the difference between the distance to the reference mirror and the distance to the temporal bone sample. If scanned along the surface of the temporal bone, a wave can be obtained that characterizes the distance from the mirror to the bone at several points. Given enough OCT scans, a model can be made from fitting a line to the calculated surface of the temporal bone. This could then be used inside of the cochlea to find a model of the interior of the cochlea.

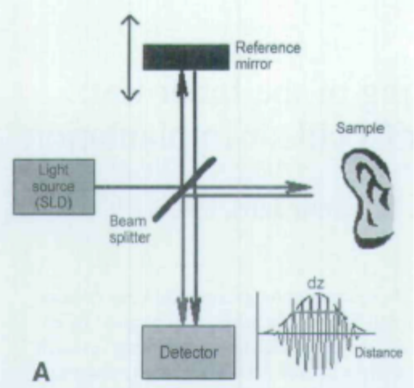

Figure 1 – OCT Diagram
Image Credit: Lin et al. [4]

D. *Virtual Fixtures*

Virtual fixtures are "algorithms which provide anisotropic behavior to surgeons' motion commands in addition to filtering out tremor to provide safety and precision" [2]. A virtual fixture is composed of a series of objectives and constraints. These are used to construct a system of equations, which are expressed with the next incremental motion of the robot. This is an optimization problem, which solves for this incremental motion of the robot and aims to achieve the objectives without violating constraints. The goal of virtual fixtures in Cochlear Implant Surgery is to help insert the electrode array along the axis of the cochlea to the correct depth. The virtual fixtures should help the surgeon to avoid bumping the walls of the cochlea with the electrode array and to avoid inserting the electrode array too deep or not deep enough. Virtual Fixtures are the main method by which a robot could assist the surgeon during cochlear implant insertion surgery.

II. PROBLEM

There are several problems with the current practice of cochlear implant insertion. Most significant of which is the lack of visibility, sensitivity of the cochlea, and precision required of the surgeon. The impact of these problems could be lessened by a robot-assisted approach to the procedure.

During the insertion of the implant, the surgeon must view the interior of the cochlea through a small window drilled during the cochleostomy. Although a microscope is used to enhance the surgeon's view of the round window, their field-of-view isn't improved and no further visibility is granted. The main source of visible feedback for the location of the tip of the implant is a mark on the electrode array, which indicates the optimal depth of insertion. Once this mark reaches the entrance of the cochlea, the surgeon begins the insertion process. This mark is created by the manufacturer of the implant, however, and so isn't based on patient-specific anatomy. Without better visibility into the cochlear interior, it is also difficult to determine whether the placement of the electrode array is optimal.

Another challenge in cochlear implant insertion is the sensitivity of the basilar membrane, which lines the cochlear interior, and the cochlear hairs. Even in patients with profound hearing loss, it is vital to protect these structures in order to preserve residual hearing. Forces on the scale of a surgeon's hand tremor may be enough to damage the basilar membrane and cochlear hairs. In order to insert the implant safely, these hand tremors must be negated.

The sensitivity of the cochlea as well as the small working space for the implant necessitate a high level of precision during the insertion procedure. If the implant is inserted or aligned incorrectly, severe damage can result and a reinsertion may need to be performed during a subsequent operation.

III. APPROACH

In order to make the cochlear implant insertion procedure safer and more repeatable, we propose a system that uses a tremor-cancelling robot to guide the implant along the axis of the cochlea to the point of insertion. Virtual fixtures are enacted based on imaging that constrain the motion of the robot to the center axis of the cochlea, guiding the implant to the ideal insertion point. This increases the chance of success for the operation, as well as minimizing the chance of cochlear damage.

The steady-hand robot is a robotic arm to which the side-view probe, bulk OCT scanner, and implant-holding tool can be mounted. It uses tremor-reduction to eliminate hand tremor and protect the cochlea. The robot is also able to enact virtual fixtures, to constrain the motion of the robot in its environment.

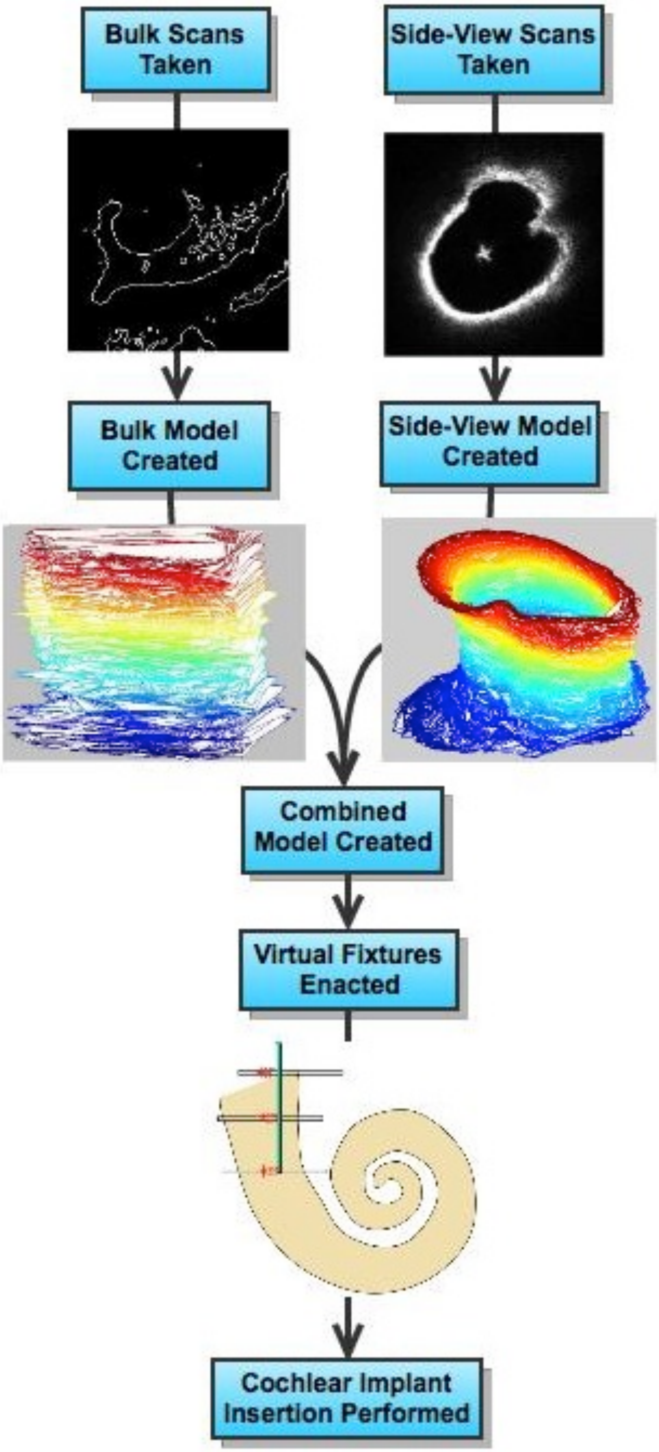

Figure 2 – Project Workflow

A. *Aims*

1. Create a model of the cochlea from an OCT bulk scan.
2. Create a model of the cochlea from B-scans taken by a side-viewing fiber.
3. Register these models together to remove error found in each.
4. Develop virtual fixtures that assist the implantation procedure.

B. *System Overview*

The system we propose consists of an OCT imaging system, bulk scanner, side-view probe, a steady-hand robot, and a computer workstation. The workflow for this system is shown in Figure 2.

1. *OCT Bulk Scanner*

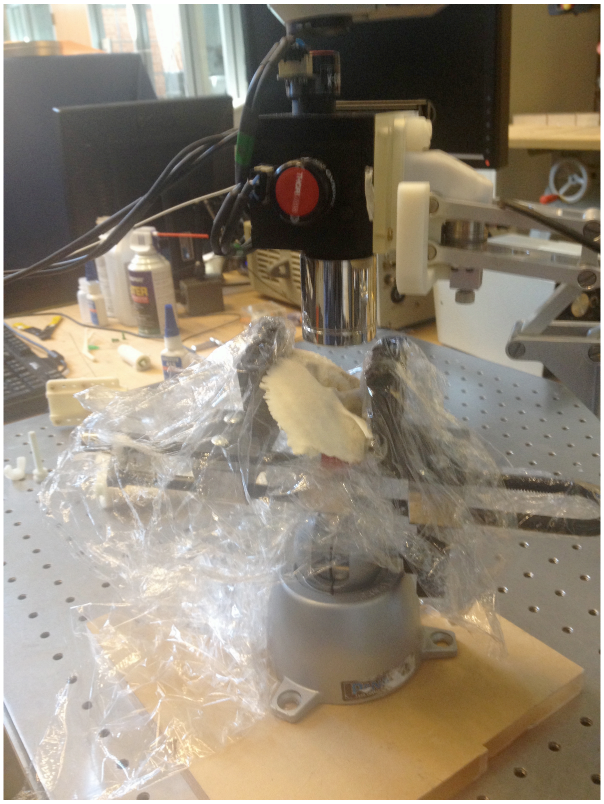

Figure 3 – Bulk Scan Setup

An OCT bulk scanner takes a 5 mm x 5 mm x 5 mm volume. This volume is taken in two-dimensional slices, each of which is made up of a number of A-scans. Each A-scan is a single, one-dimensional row of the slice. The slices are composed into a single volume cube. The size of one volume isn't sufficient to capture the entire cochlea, so several are taken and then the images are stitched together. This stitched volume can then be used to create a model.

To create the model, each slice of the volume is analyzed with an edge-detection algorithm to find the contour of the cochlear wall. An example of this edge-detection can be seen as the output of “Bulk Scans Taken” in Figure 2. These contours are stacked based on depth information and used to create a triangular mesh, which can be seen as the output of “Bulk Model Created” in Figure 2.

In order to solve for the transformation between the coordinate system of the steady-hand robot and that of the OCT volume, the robot must be calibrated by taking several bulk scans of a fiducial marker. This calibration target is fixed onto a flat surface, and the scanner is aligned so that the volume fully encompasses the object. These volumes are then processed to identify the locations of several key points on the fiducial marker in the OCT coordinate system. These points, as well as the pose of the robot for each scan, are saved and used to set up a system of “AX=XB” equations.

In this system, there are two known transformations and two unknown transformations:

$$
\begin{aligned}
F_{RO}&(Robot\ to\ OCT)(unknown) \\
F_{Oi}&(OCT\ to\ fiducial)(known) \\
F_{BA}&(Base\ to\ fiducial)(unknown) \\
F_{Ri}&(Base\ to\ Robot)(known)
\end{aligned}
$$

$$F_{BA} * F_{Oi}^{-1} = F_{Ri} * F_{RO}$$

A coordinate system is created in the center of the fiducial marker. The transformation between the OCT coordinates and this newly created fiducial coordinate system can be simply calculated if the location of the marker in the volume is known. One such transformation is calculated for each volume taken and the i^{th} is denoted as F_{Oi}. There is a corresponding series of base to robot transformations for each volume, which transforms a given vector from the robot’s base coordinate system to that of its end-effector. In order to solve for the robot to OCT transformation, the unknown base to fiducial transformation is eliminated from the equation as follows:

$$
\begin{aligned}
F_{BA} &= F_{R0} F_{RO} F_{O0} \\
F_{R0} F_{RO} F_{O0} F_{Oi}^{-1} &= F_{Ri} F_{RO} \\
F_{Ri}^{-1} F_{R0} F_{RO} &= F_{RO} F_{Oi} F_{O0}^{-1} \\
A &= F_{Ri}^{-1} F_{R0} \\
B &= F_{Oi} F_{O0}^{-1} \\
X &= F_{RO}
\end{aligned}
$$

Once A, B, and X are identified, a system of equations consisting of AX = XB for each value of i is then constructed. To solve for X, the desired transformation, the quaternion-based method is used. Once the frame of the OCT system is known in robot coordinates, the relative location of objects in the bulk scan volumes can be related to the position of the cochlear implant. This enables surgeons to use the volume as a guide in the insertion of the cochlear implant.

2. *Side-view Probe*

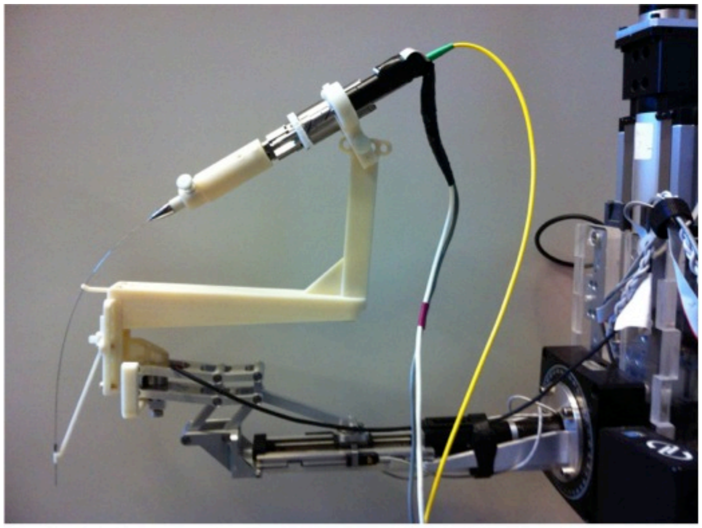

Image Credit: Berk Gonenc

Figure 4 – Side-View Probe Setup

A side-viewing probe mounted to a motor is inserted into the cochlea and rotates to capture a B-scan image of the wall of the cochlea from the inside at a particular depth. The probe uses an angled fiber to capture OCT A-scans. Each of these A-scans represents the distance between the probe and the wall of the cochlea at one position along its rotation. Approximately 10,000 A-scans are taken per complete rotation of the probe, and these scans make up one B-scan. An example of a B-scan can be seen as the output of “Side-View Scans Taken” in Figure 2. B-scans are taken at several different depths into the cochlea. The contours obtained from these B-scans are stacked based on depth information and used to create a triangular mesh, which can be seen as the output of “Side-View Model Created” in Figure 2.

There are two types of calibration that are necessary to relate the position of the probe to robot coordinates. The first calibration performed is a translational calibration. The simple pivot calibration is performed using the tip of the probe. This gives us the displacement between the robot frame and the tip of the probe. The second calibration is a rotational calibration. This calibration determines the rotation part of the transformation from the robot to the probe by measuring the angle between the robot frame and the probe’s vertical axis.

A third calibration uses a calibration object, the B-scan of which can be seen in Figure 5, to align the image of the B-scan with the axes of the robot. It does this by using the dimple in the calibration object as a reference for the +y axis of the robot.

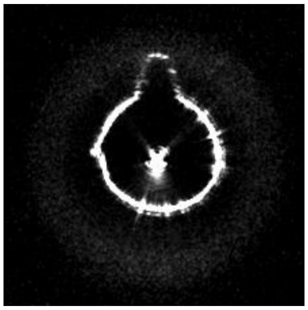

Figure 5 – B-scan of Calibration Object

3. *Combined Model*

Each of the models generated from the two imaging methods mentioned above has strengths and weaknesses. The bulk scan captures the area around the cochlea as well as the bottom of the basal turn well, but doesn’t have much detail in the cochlear walls. The side-view model, on the other hand, can see the cochlear walls with greater detail, but lacks the ability to visualize the basal turn as effectively as the bulk scanner. In order to fill in information that is missing from each of these models, we use an ICP algorithm to find the transformation between the models. The contours from each model are averaged to create a combined model, which is used to enact virtual fixtures.

4. *Virtual Fixtures*

We implemented two virtual fixtures that will assist in inserting the implant. The first virtual fixture assists in guiding the side-view probe to the basal turn. As contours are obtained from the probe’s output, the center of the cochlea is identified in each. The vector from the current position of the probe to the center of the cochlea is identified at several depths, and the virtual fixture is set up to minimize these vectors. For each of these contours added to the virtual fixture, an objective is created so that the point on the probe at the same depth as the contour is incrementally moving towards the computed center of that contour. When it is enacted, the virtual fixture lines the probe up with the axis of the cochlea. The user can then guide the probe along this axis to capture the side-view scans necessary to create the side-view model.

The second virtual fixture uses the combined volume to guide the implant to the desired insertion point. The model is broken up into contours, which are used to set up a virtual fixture that minimizes the distance from the implant to the cochlear axis the same way as the first virtual fixture. Once the implant reaches the desired position, the robot halts all motion so the insertion can be performed.

Figure 6 – Insertion of Cochlear Implant into Phantom

IV. RESULTS

In order to determine that our system was functioning correctly, we set up a series of experiments with the cochlear phantom and a dry temporal bone. In the phantom, a side is cut away so a USB camera can record the interior of the phantom. We tested the side-view virtual fixture in the phantom, ensuring that as we inserted the probe, the virtual fixture guided it to the center axis. From the camera feed, we could tell that the probe didn’t touch the sides of the phantom and was aligned with its axis. We then took a bulk scan of the cochlea in the dry temporal bone, and repeated the side-view probe experiment in the dry bone. Once we had models from both imaging methods, we used our ICP registration to create a combined model and tested our insertion virtual fixture with it. We were able to constrain motion to the cochlea’s axis and halt once we were nearing the basal turn.

V. SIGNIFICANCE

This project is significant because cochlear implant insertion is a difficult procedure that has widespread use. As of December 2010, 219,000 people worldwide use cochlear implants [6]. The market for cochlear implants is large, and several companies are working to develop cochlear implants that are easier to insert. Cochlear Ltd. is a company that is working closely with ERC CISST to develop implants suited to a robotic system for this insertion, and their investment of time, effort, and resources showcases the potential effect this system can have once implemented. Support of this project by Cochlear and Core NSF CISST/ERC helps to ensure that the goals of this project will be realized. The methods used in this project also have potentials applications to other surgical procedures, as they increase the overall safety of the surgery by constraining the movement of the robot.

Management Summary

I. DIVISION OF LABOR

Paul primarily worked on the side-view and combined models, as well as the virtual fixtures. Emily primarily worked on the bulk model and combined models. Both team members worked on project planning, documentation and presentations.

II. ACCOMPLISHMENTS

Our minimum deliverables for this project were separate OCT bulk can and side-view probe models, and a working side-view virtual fixture. Our expected deliverables were a registration overlay of the OCT bulk scan and side-view models, and a working insertion virtual fixture. Our maximum deliverables were a fine-tuned combined model presentation for intraoperative use, and a complete, working, user-friendly system. We completely finished our minimum and expected deliverables for this project and made some steps towards completing our maximum deliverables. Beyond performing the registration overlay of the bulk scan and side-view models, we began to fine-tune the combined model by eliminating redundancies. We have yet to make this system more user-friendly for use by surgeons, but we do have some user documentation.

III. FUTURE WORK

As work on this project proceeds, there are several big steps to be taken before the system can be implemented clinically. The process for creating the side-view probe must be improved to ensure that the fibers are more durable and return a stronger signal in wet bone. The side-view probe currently works well in dry bone, but less so in wet bone, so it is more difficult to create a model from B-scans taken in wet bone. Once a probe can be constructed that performs better in wet bone, then data should be taken from a wet temporal bone. In addition, the probe is susceptible to breaking with sudden movement because of the high tension on the fiber inside the probe. The next step in this project is to improve the combined comprehensive model. Currently, the combined model is based only on averaging the registered bulk and side-view models. In the future, a smarter method for combining contour data could include using the data from only one of the separate models at depths where that data is known to be more accurate, such as the bulk model data near the basal turn. Additionally, in order to streamline this system for clinical use, it would be valuable to get input from a surgeon who regularly performs cochlear implant insertions. Paul will continue to work on this project in Fall 2013.

IV. LESSONS LEARNED

- Familiarity with OCT imaging and virtual fixture constrained optimization algorithms.
- Communication among members of the research team and owners of project dependencies is vital for success.
- It is important to be flexible with any project timeline as difficulties are bound to arise.

V. ACKNOWLEDGEMENTS

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