3D Ear Scanning Enables a Platform for Wearable Computing

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Abstract

The ear and ear canal present exceptional challenges for 3D scanning technology. In addition to the typical challenges associated with scanning body parts (dynamic/moving components, large skin composition variability, etc.) the unique challenges of the ear and ear canal include the limited diameter of the canal, hair and wax interference, and sharp bends and undercuts in the shape of the canal itself. Although navigating and acquiring data within this small skin covered cavity are challenging, the impact of such technology has large implications across a range of industries (medical, military, industrial, aerospace, music, and consumer electronics). Herein, we describe the design, calibration, use, and experimental results of a non-invasive, in ear, 3D scanning system ("eFit"). The eFit ear scanner allows for rapid, real-time modeling of the human ear - both the ear canal and outer ear. This technology has been validated across thousands of individuals with a volumetric scanning accuracy of better than 90 µm. The design and production of a custom in-ear product utilizing data from the eFit scanner is also described to further establish use cases of 3D ear scanning.

Keywords: 3D Ear Scanning, 3D Printing, Wearable Computing

1. Background

Small (50mm diameter or less) interior surfaces have been a challenge for conventional 3D scanners. 3D scanners are typically architected to have large (~10mm+) optics with a large baseline. Large optics are cheaper to manufacture and easier to calibrate and large baseline increases scanner accuracy. This architecture limits the ability to scan interior or complex surfaces. In particular, the ear has proven extremely difficult to 3D scan. The canal is small in diameter, with an average major axis of 6mm and minor axis of 4mm. In addition, the canal has sharp bends, and contains hair, wax, and oils. When these unique challenges are combined with the typical challenges associated with scanning the human body (skin tone variability, subdermal scattering, and the dynamic nature of the human body itself), it is easy to understand why a precise, accurate 3D ear scanner has been difficult to develop.

Previous attempts to map the ear via 3D scanning have met with limited success. For instance, one approach to solve the challenge of scanning small diameters has used off the shelf endoscopes, with field of views suitable only for forward looking reconstruction, or right angled reconstruction. [1] However, solely forward looking views are not suitable for tight bends or undercuts in the canal and concha bowl and similarly, right angled reconstruction requires rotation of the probe tip or, if handheld, the scanner itself. In an approach to dealing with the issues posed by skin, hair, and wax, the surface to be scanned was covered with a thin, inflatable membrane [2]. Unfortunately, this solution creates further, unrecoverable, challenges. The membrane is difficult to inflate such that all desired features can be measured. Additionally, the membrane also obscures the natural resting state of the body and moves relative to both the subject and operator, further confusing the measurement. A different approach to scanning involving light reflection via mirrors does successfully measure the superficial layers of the epidermis. [3] However, this complicated system requires moving mirrors that are large and difficult to miniaturize. In addition, acquiring full coverage of the ear canal and pinna (the outer visible portion of the ear) involves registration and subsequent stitching together of individual patches or sections of the ear, potentially increasing incremental errors. As the naturally occurring curvature of the ear is large relative to patch size, registration error between patches is consequently also large. These registration errors stack as the full scan is completed, making this system of tracking and registration impractical for scanning ears. Since the ear canal is tortuous and widely varied from individual to individual, a system is needed to guide the scan operator into and out of the ear. None of the previous 3D ear scanning technologies have included an adequate ear canal navigation system; there are no guides for the user to follow to comfortably enter the ear canal and no guides to ensure appropriate features are scanned.

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Herein, we describe the creation of a 3D ear scanner that answers all the above described needs. The eFit ear scanner utilizes 3D scanning technology on the microscale, allowing for accurate and precise measurement of complex holes in small-scale cavities. This scanner furthermore allows for easy navigation of the ear canal by the operator. To our knowledge, the eFit scanner is the first ear scanner that combines all the required elements to obtain an accurate, complete scan of the canal, concha, and helix.

2. Methods

2.1 Scanner Architecture

The eFit scanner system is composed of a three-camera handheld portable ear scanner, a tracking fiducial headpiece, and a scanner cradle that also serves as the calibration validation artifact. Figure 1 is an image of the handheld eFit Scanner. Of the three cameras on the handheld portable scanner, the center camera is used for reconstruction and the two cameras to either side of the center probe are used for tracking the position of the scanner relative to the subject's head. The scan operator moves the scanner into and out of the ear, using real time navigation cues to appropriately position the scanner for data acquisition. A graphical user interface is used to step the user through the scan process. The user interacts with the GUI through a touch screen LCD integrated in the handheld scanner and a trigger. A mouse and keyboard can alternately be used for data input and manipulation.

Figure 1.The eFit 3D ear scanner includes a radial 3D scanner for the ear canal and under cuts in the pinna, a line scanner for the flat regions of the pinna, two tracking cameras, a video otoscope, and an integrated LCD.

2.1.1 Radial Illumination

Light in the form of a ring is used to scan the ear canal and undercut regions of the pinna. This ring of light is generated through a radial illumination system that surrounds the center camera optics. Light is generated at the proximal end of the device and is transported to the distal end within a cylindrical light guide. A sectioned cylindrical dichroic cone is used to reflect the light, generating a ring of illumination at the distal end of the probe. The sectioned cylindrical dichroic cone is positioned 4-5mm distal of the first element of the center cameras' optics. In this way, the center camera looks through the cylindrical light guide and will see the laser if it is incident upon skin within the working range of the system. The distance between the sectioned cylindrical dichroic cone and the first element of the center camera optics system also serves as the baseline of the radial 3D scanner (Figure 2). This area could also be called a "window" in which the camera observes the laser.

Figure 2. Distal end of the eFit scanner shows the cylindrical light guide, the distal end of the center camera optics, and the sectioned cylindrical dichroic cone

2.1.2 Line Illumination
A line generator is positioned at on the device at the proximal end of the probe. A line is projected forward, towards the tip of the center camera. The line is slightly angled towards the tip of the center camera/ probe to create a baseline of 4-5mm.

2.1.3 Center Camera Optics
Small diameter wide angle low distortion lenses were custom designed for this application. The lenses are 2.3mm in diameter and there are ten elements in the system which have an overall length of 55mm. The nominal field of view (FOV) of the lens is 125°.

2.3 Scanner Calibration

To enable real-time reconstruction, a look up table (LUT) is generated for each of the laser systems (radial and line). The center camera is used to acquire an image of the laser. The 3D position of every pixel (where there can be valid laser data) is mapped relative to the three camera system in the LUT. This will generate a planar section of point data where the laser is incident upon the scanning subject's skin relative to the current position of the scanner.

2.4 Image Processing

The baseline and the field of view of the center camera define the working range of each of the laser systems. The center camera views the skin through the “window” of the center camera. An image is captured of the laser for analysis through image processing. The image processing algorithm identifies the laser incident upon skin. Once the laser is identified, the algorithm finds the theoretical center of the laser. Subpixel accuracy is desirable in this step. Since laser is specular and skin is randomly patterned and fragmented, a high level of smoothing is helpful. By finding the average brightness of the laser, the algorithm can threshold the image to segment the image into candidate laser and non-laser regions. Additional algorithms are used to validate that candidate regions are indeed laser by looking for laser characteristics vs noise. Next the software finds the center of the validated laser regions. Then the 3D position of the laser is calculated by referencing the LUT. In some situations interpolation is necessary between pixels in the LUT. The results are a series of 3D points that lie in a plane at the center of the laser intersecting the subject's skin, which appear in 3D space as cross sections or strips of point data (planar section of point data, see Figure 3). These strips will later be oriented relative to a stationary headset mounted to the subject's head.

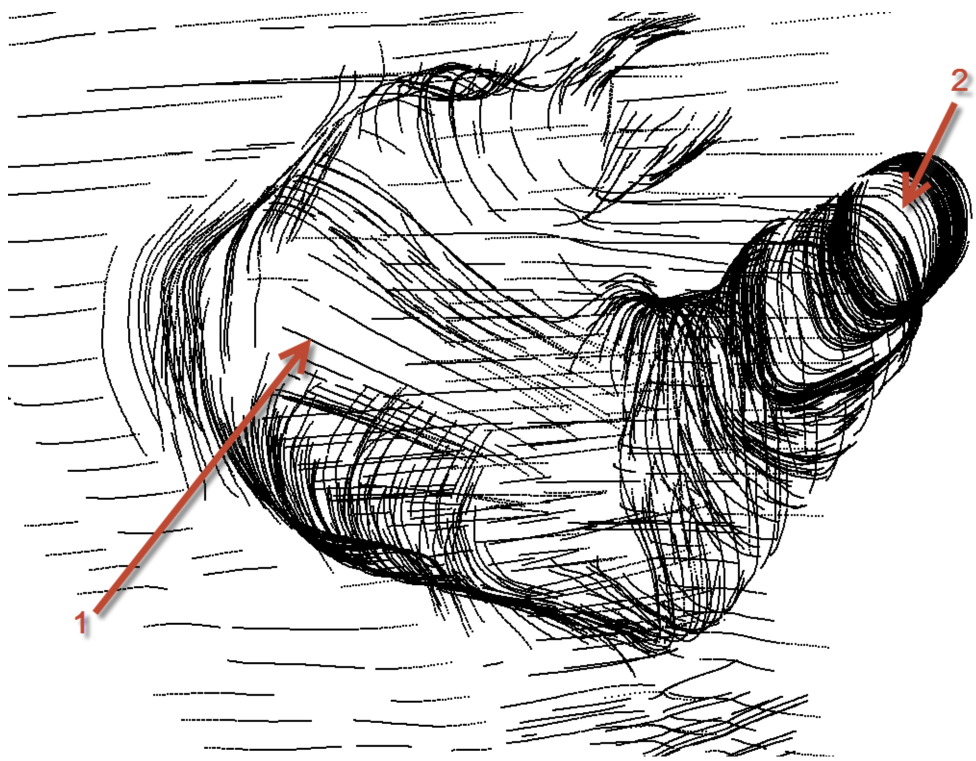

Figure 3. Point data from the eFit scanner before it has been processed into a mesh. (1) Indicates an example of planar section of point data from the 3D line scanner (2) indicates an example of a planar section of point data from the radial illumination 3D scanner.

2.5 Integrated Tracking

To map consecutive slices together, a system that can track the position of the scanner relative to the subject's head in real-time is necessary. This is accomplished with two additional cameras mounted to either side of the center camera and a headset with integrated fiducial rings worn by the subject. Each fiducial ring has a series of dots in a De Bruijin sequence [4] such that any seven consecutive dots are unique. The dots are printed on a flat metal ring with high contrast paint. The pattern is accurately printed, such that if either camera observes and decodes seven consecutive dots, even lacking visual overlap on the ring, the handheld can accurately resolves its position. The fiducial ring is illuminated with IR to provide consistent contrast for target identification without visible strobing to the operator or subject. During initial calibration of the scanner, the intrinsic and extrinsic parameters of all three cameras are computed simultaneously relative to each other. The construction of the scanner is such that all three cameras will remain fixed, relative to each other. A validation object is included in the scanner's cradle to verify that the cameras have stayed in their original position (within a small tolerance) before every scan that is taken. Since the intrinsic and extrinsic parameters of each camera are accurately known, the planar sections of point data in the center camera LUT can be translated and rotated based on the position of the three camera system relative to the subject worn headset fiducial. Each strip of point data is sequentially re-oriented to "headset space" generating a point cloud.

2.6 Real Time 3D Rendering

To enhance visual perception of the data, a real-time triangular mesh is generated from the point data. This is accomplished in a multistep process, where the planar sections of point data are initially passed through a voxelization and smoothing algorithm. Voxelization is used because the point sections are generally denser in the planar direction than they are in the translation direction (direction of motion of the handheld). The result is a smoothed, ordered series of points that represent a surface. The normal of the surface is computed, and triangles connect the points in order to orient the interior and exterior surfaces. This orientation is subsequently visually represented with shading, colors, and transparency. The mesh is computed in near real-time at approximately one frame per second to aid in navigation and to ensure that a complete set of data is acquired from the ear.

2.7 Augmented Reality Navigation

One of the biggest technical challenges with scanning the ear has proven to be successful navigation of its complicated internal structures. This implies safe navigation to the appropriate depth, aligning the probe for optimal orientation axially, and maintaining the distal end of the center camera at the appropriate distance away from the skin within the working range. Real-time meshing and display of the data guides the user to areas that need to be scanned as well as providing spatial feedback. The primary navigation tool within the ear canal is the real-time video otoscope, which displays a video stream of the interior ear canal. This is accomplished by alternating illumination methodology within the canal. The center camera is capable of illuminating the ear canal with alternating white and blue light. The center camera initially illuminates the canal with white, highly divergent, light, immediately followed by the blue, non-divergent light (radial illumination) used for reconstruction. The GUI displays the white frames in a video stream to the operator, providing visual feedback. To aid with navigation, an augmented reality overlay of the blue frame image processing is applied to the white frame video stream. This augmented reality stream accomplishes two objectives: it allows the operator to move into and out of the ear while keeping the probe tip axially centered, and it provides the user with near real-time information of what data is being captured. Knowledge of the current data being captured displayed in near real-time, coupled with the near real-time mesh, guides the user to appropriate angles and positions necessary to capture data in areas hidden from normal / direct line of sight (Figure 4).

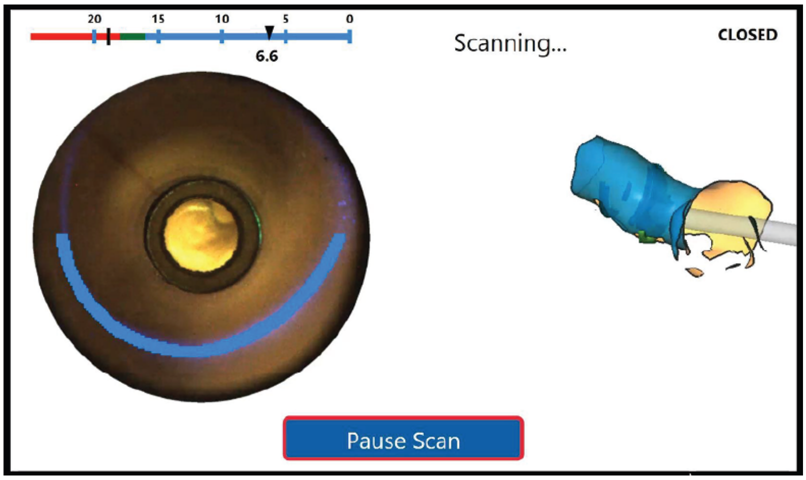

Figure 4. Augmented reality navigation coupled with real-time 3D rendering. On the left of the screen is a live view of the inside of the ear canal (the white light illuminated video stream). Overlayed on the video stream is a blue line, which indicates where data is being collected from the previous radial illumination image. On the right side of the screen is the near real-time 3D rendering of the ear scan.

3.0 Results

The eFit scanner is currently being used in several applications, including medical, military, industrial, music, and consumer electronics. Many thousands of people in various situations on three different continents have been scanned and their ear canal models have been rendered. Sample data of an ear canal can be downloaded at http://efitscanner.com/#data

3.1 Volumetric Accuracy

A validation block with a cylindrical bore was measured with a Hexagon Metrology Optiv Classic 321GL tp CMM. The quoted accuracy for the CMM is 0.8µm [5] over 10mm. The validation bore had a CMM measured radius of 4.0205mm. The validation bore was measured with 5 eFit scanners 5 times each for a total of 25 measurements of the bore. Figure 5 shows the average bore radius measured with each scanner compared to the nominal as measured with the CMM.

When all 25 measurements are considered at once we show the eFit measured radius as 4.0258 mm +/- 0.028 mm with 99.7% confidence. As such, the overall average error compared to the nominal value was 0.00535 mm (4.0258-4.0205 = 0.00535). The largest error from the nominal value for a single measurement was 0.01879 mm with scanner 5. The smallest error from the nominal value for a single measurement was 0.00018 mm with scanner 2.

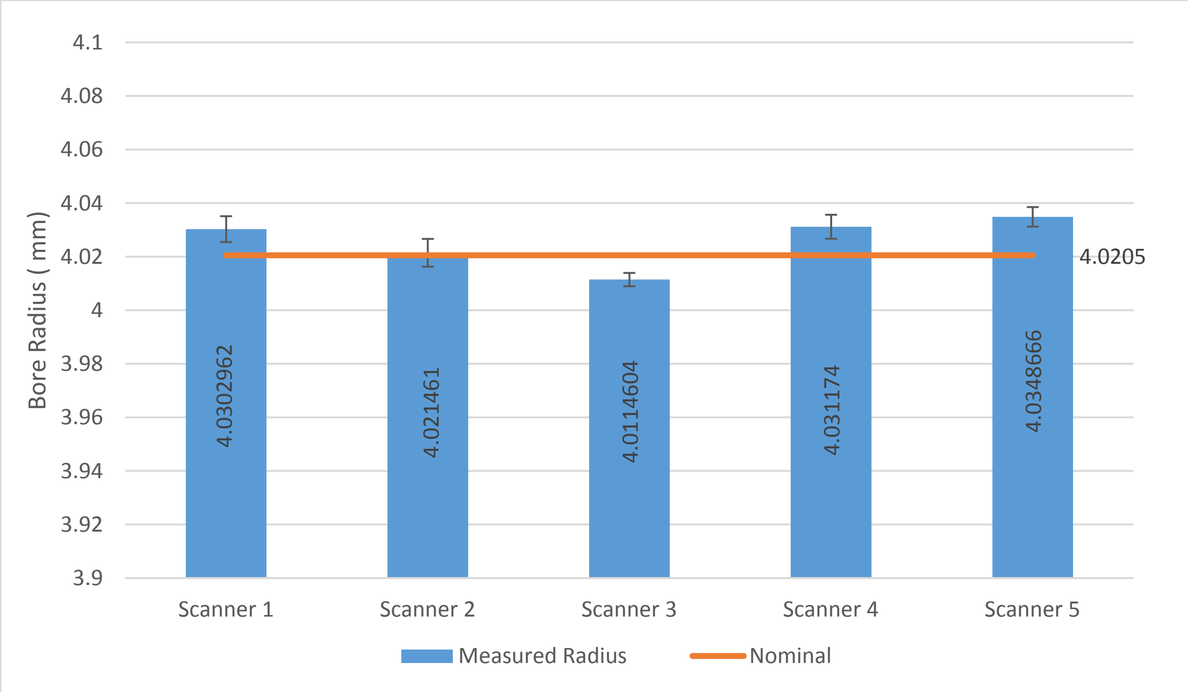

Figure5. eFit scanners are accurate compared to a nominal value. Five eFit scanners measured a cylindrical bore of known radius. The scanners were accurate to the nominal value within a range of 0.028mm.

3.2 Scanner Repeatability

Each scanner's measurements are highly repeatable. As shown below in Table 1, when each scanner is analyzed individually, the variance within each scanner is lower than the variance across multiple scanners. Although this is not surprising, it validates the measurements listed above, demonstrating the high precision within each unique scanner's measurements.

	Average Measured Radius (mm)	Standard Deviation (mm)
Scanner 1	4.0303	0.0049
Scanner 2	4.0215	0.0052
Scanner 3	4.0115	0.0025
Scanner 4	4.0312	0.0045
Scanner 5	4.0349	0.0036
Avg for all Scanners	4.0259	0.0094

Table 1: eFit scanners are highly precise, showing low variance on bore gage measurements. Each scanner was tested in five trials; the scanners demonstrated high repeatability in scanning with an average error between scans of 0.0053 mm.

4.0 Conclusions

We present a method for measuring complex, interior cavities with high accuracy and precision. This method combines the principles of 3D laser scanning, radial illumination, image processing, and augmented reality to create a novel, easy to use handheld scanner. The eFit scanner has been validated across both established measurement parameters as well as thousands of human patients. Validation tests have demonstrated both high repeatability within individual scanners and high accuracy against known standards. The ease of use and speed with which this scanner operate allow highly customizable wearable devices to be created for users within in a variety of environments. The eFit scanner has been accepted and is in use in established markets for custom in-ear devices. The eFit scanner will have an even greater impact in nascent technology, such as wearable computing.

4.1 In-Ear Biometrics

The 3D ear scanner enables a multitude of biometrics that were once impractical or impossible for use in wearables. The ear provides a nest for sensors near the brain. Sensors enabled by custom ear scans include electrodes, optical pulse oximeters, microphones, and accelerometers, among others. Due to the ear's complex geometry and the ear scanner's ability to accurately capture it, the custom devices rest securely in the ear and make consistent, comfortable contact with the skin. Sensor-skin surface area is maximized and motion artifacts are reduced, enabling high signal to noise ratio (SNR) measurements. For example, custom ear devices with electrodes are able to capture nearby signals including auditory evoked potentials (AEPs) and alpha, beta, and delta waves via electroencephalography (EEG). Electrodes configured for electromyography (EMG) in the ear are able to detect bruxism and food intake by measuring craniofacial muscle activity. Heart rate can be detected in the ear using electrocardiography (ECG) across the head, optically via pulse oximetry, or acoustically through the sealed ear canal. Microphones can be used to detect transient and evoked otoacoustic emissions, talking, and snoring, while accelerometers can detect movement, steps, head position, etc. A few applications include sleep monitoring, attention and stress monitoring, biometric authentication, caloric intake approximation, and bruxism biofeedback. To further demonstrate the impact of in-ear 3D scanning on wearables, the creation of an in-ear wearable device with integrated biosensors is described below.

4.2 In-Ear Device Design & Manufacturing

The result of the ear scan is a 3D mesh generation (STL file) for use in CAD software. Though not required for manufacturing, two prominent software packages were developed specifically for designing custom in-ear devices by 3shape and Cyfex. The original intention of these packages was for sculpting 3D-scanned silicone ear impressions for hearing aids. For example, Cyfex simplifies trimming of the scan and placing of components through semi-automation. The user can create templates for subsequent application to ear scans which aid in quick production of 3D-printable CAD models, enabling scalability and mass customization.

4.2.1 General Design Considerations

The final mesh must undergo operations to create a comfortable in-ear device that effectively achieves the desired functions. The designer begins by expanding the scan, scaling it by 250μm for example, which ensures retention of the device in the wearer's ear. Next, the prominence of the helix lock is reduced to aid in insertion and increase comfort. An offset thickness of 350μm is added around the first bend of the canal, creating an acoustic seal within the canal blocking sounds from the environment for the user. Thickness at the first bend may be varied to balance noise isolation and comfort. The 3D ear scanner can be used to obtain scans that extend deep past the second bend of the canal, though the product should typically not extend deeper than second bend due to the heightened skin sensitivity in this region. An operation is performed to cut the scan and round its tip to ease insertion and prevent irritation. Next, the scan is extended a desired distance away from the ear to create space for housing electronic components. Ports may be added to direct audio toward the tympanic membrane while sensor ports may control precisely where the sensor should gather data. Cyfex enables precise placement of electronic components and verifies that space requirements are met. Figure 6 provides more details on this process.

4.2.2 3D Additive Manufacturing

Material of the end product must also be considered while selecting the 3D manufacturing process. Devices must be designed specifically with the intended 3D printing technology in mind to optimize the speed, accuracy, and surface quality. Stereolithography (SLA) and direct light projection (DLP) technology are typically used to create accurate, high quality ear devices using photo-sensitive resins such as acrylates. For applications where accuracy and surface finish are a priority, SLA and DLP printing are recommended over other available printing methods. It is also possible to use fused deposition modeling (FDM) technology with polylactic acid (PLA) for faster manufacturing, though both accuracy and surface finish may not be sufficient for some applications. To create a soft end product, a mold may also be designed and printed for the purpose of injecting an addition-vulcanizing silicone rubber. After printing, a smooth, aesthetically pleasing surface may be created using a specialized biocompatible lacquer.

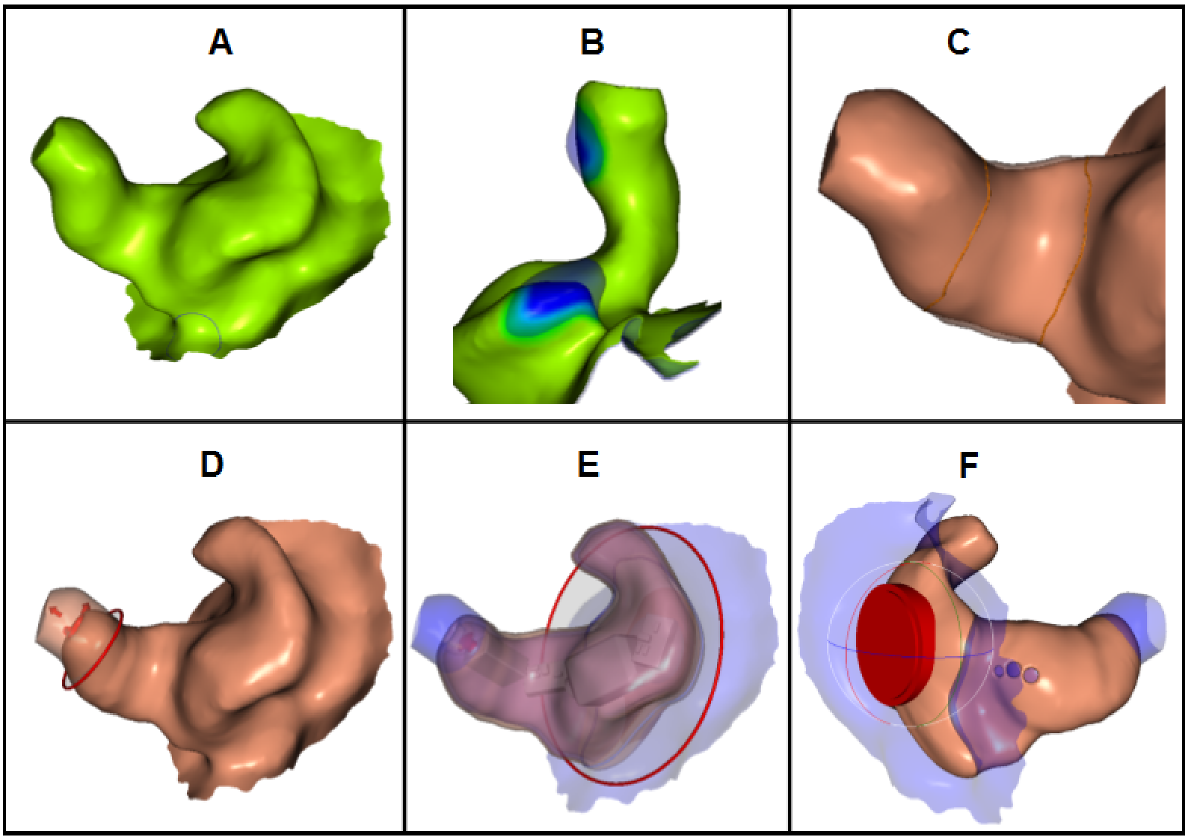

Figure 6. General Design of In-Ear Devices. A few good practices are recommended to creating comfortable and effective in-ear devices. (A) The original STL mesh depicts the surface of the skin. (B) Material is removed from the canal's second bend and helix lock. These modifications make device insertion easier. (C) Thickness is added to the canal's first bend which serves to create an acoustic seal and prevent leakage. (D) The scan is cut in order to create the canal tip of the device. The second bend approximately marks the beginning of the skull and its thin, sensitive layer of skin. Depending on the application, most devices should not go past the second bend. (E) The scan is cut and extended away from the ear, to what is called a faceplate. This step creates a solid shell that is no longer an open surface. Electronics placement can be simulated in this step. The software employs automatic collision avoidance which simplifies simulation within limited space. (F) Predefined parts can be added or subtracted at this step. Acoustics exits, cable exits, sensor ports, and fasteners can be added to the shell. These may be created and imported from other design software such as SolidWorks.

4.2.3 Example Custom-Fit In-Ear Wearable with Integrated Pulse Oximeter

Before designing an in-ear device, the required architecture must be considered (Figure 7). For a wearable that delivers audio while measuring heart rate and blood oxygenation, the size and placement of the pulse oximeter and acoustic transducer along with the placement and characteristics of the electronics must be considered. Miniaturization of microcontrollers, Bluetooth transceivers, batteries, LEDs, sensors, and speakers has enabled the wearable system's full integration into an earpiece.

Building electronic components into a pre-assembled module provides quick custom scan-to-product manufacturing. This may be done using a flexible or rigid-flex printed circuit board (PCB) along with fastening features that allow for quick integration into the custom geometry of the earpiece. Balanced armature acoustic transducers are typically used over dynamic transducers due to their small size, limited or no requirements for venting to a back volume of air, and excellent frequency response in a sealed canal. The above described wearable is just one example of an in-ear product made possible by this technology, many more customizable products will be possible across a multitude of fields as this technology is adopted.

In conclusion, the ear canal is an extremely challenging environment for 3D scanning but the ear offers a great deal of promise for various industries. Scanning the ear directly has already revolutionized existing markets for custom in-ear devices and this enabling technology will provide a platform for the future of wearable computing.

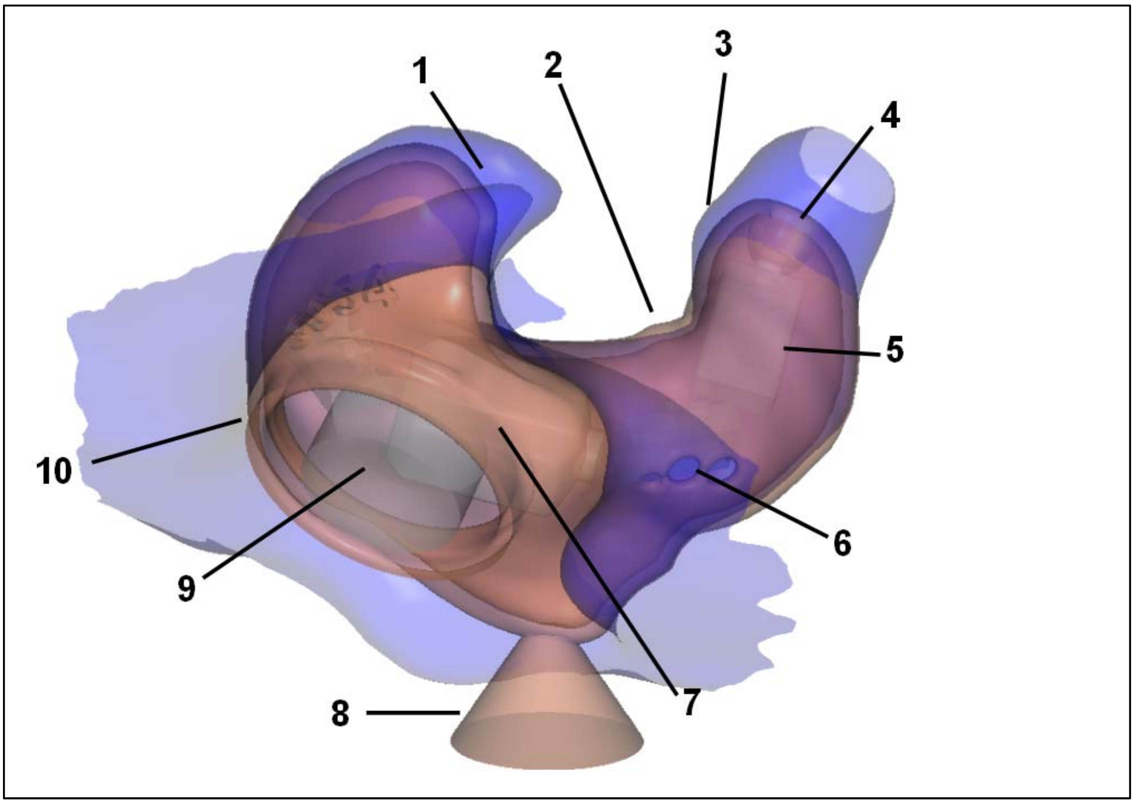

Figure 7. Final CAD model overlaid on the original 3D scan. Features added in CAD software include (1) helix lock reduction for easy insertion and comfort, (2) added thickness to the first bend for an optimized acoustic seal, (3) reduced and rounded canal tip for easy insertion and comfort, (4) sound port placement directed toward the tympanic membrane, (5) placement and fit verification of the balanced armature acoustic transducer, (6) placement of the pulse oximeter and its sensing ports, (7) positioning of a cable exit, (8) support intended for a UV DLP acrylate printer, (9) placement and fit verification of modular electronics within the concha, and (10) extension of the device away from the ear to create room for components.

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