A Tele-Immersive System for Surgical Consultation and Implant Modeling

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1 Background

Disease and activities related to modern living have resulted in an increase in the number of injuries with large cranial defects. Today, major causes of large cranial defects include: trauma (motor vehicle accidents, occupational injuries, urban violence, sports injuries and war), infection, tumor, and miscellaneous causes (aneurysms, subdural hematoma, cranial decompression, cranial nerve neuralgias). [1]

The specialization of neurological surgeons along with the need for medical modelers makes it very difficult to assemble the expertise necessary to repair large cranial defects. Large-scale health emergencies that may include interruption of transportation and other infrastructures will make it even more difficult to gather the expertise and personnel to perform these critical procedures. Even in the best of times and with the best resources, the design, fabrication and implantation of large cranial implants has many problems including poor fit and long operating room times.

In 1996 a new semi-automated technique for creating cranial implants was pioneered by Dr. Fady Charbel, Ray Evenhouse and their team.[1] These custom-fitting cranial implants are made prior to surgery using the patient's CT data, resulting in a near-perfect fit. As shown in Fig. 1, a computer model of the skull and defect is generated from the CT data. This polygonal data is sent to a rapid prototyping stereolithography machine, where a physical model of the skull with defect is made. This model serves as a template for the manufacture of the implant. A dental grade wax is used to fill the negative space in the model representing the skull defect. A mold is made of the wax pattern, filled with medical-grade PMMA and cured in a hot-water bath. After trimming and polishing, the implant is sent to the operating suite for ethylene oxide gas sterilization. During the operation a skin flap over the defect is undermined and dissection continues until the edges of the skull defect are exposed. The implant, which fits precisely is secured in place with a minimum of three or four titanium plates and screws. The incision is closed.

A nine-patient study was conducted using the technique described. The use of patient-specific stereolithographic models permits the manufacture of implants with near perfect fit and complex geometry which intra-operative reconstruction techniques are not able to duplicate. [3]

However this method is expensive and time consuming because many traditional sculpting steps such as physical sculpting, mold making, and defect stereolithography are involved. Consultation between surgeon, patient, and modeler is often difficult, and implants often take weeks to produce.

The major goal of this research is to develop a networked collaborative surgical system for tele-immersive consultation, surgical pre-planning, implant design, post operative evaluation and education. The system is designed to mimic the traditional working environment as closely as possible, replacing the time consuming and expensive steps in the process (such as sculpting, mold making, and defect stereolithography), and providing more functionality for the users.

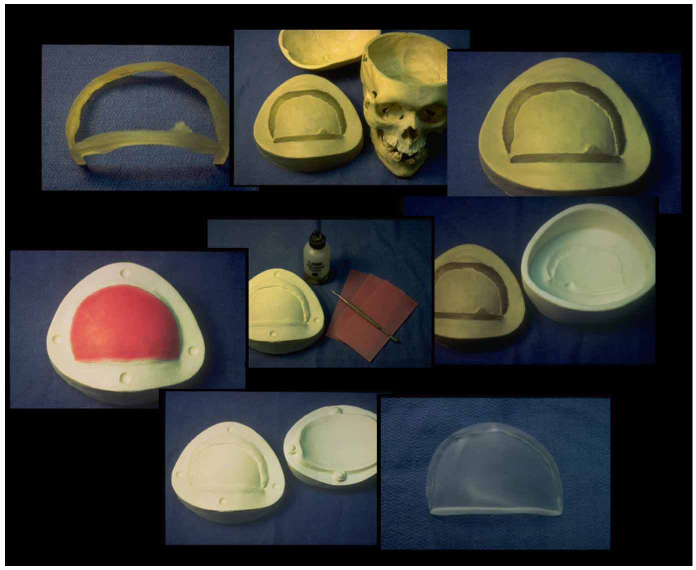

Figure 1: Implant design method developed in 1996.

2 System Design

Our strategy to build a cutting-edge biomedical modeling system is to make use of advanced networks, advanced visualization techniques, and computer-controlled rapid prototyping systems. The biomedical modeling system is a networked tele-immersive collaborative surgical system for surgical pre-planning, consultation, implant design, post operative evaluation, and education.

Tele-immersion enables users in different locations to collaborate in a shared, virtual, or simulated environment as if they are in the same room. It is the ultimate synthesis of networking and media technologies to enhance collaborative environments. Tele-immersive applications combine audio, avatars (representations of participants), virtual worlds, computation and tele-conferencing into an integrated networked system.[4]

As shown in Fig. 2, the process of implant design begins with CT data of the patient and the Personal Augmented Reality Immersive System (PARIS^{TM}). The implant will be designed by medical professionals in tele-immersive collaboration. In this design process the medical modeler creates a virtual implant that precisely fits a defect generated from patient CT data. A haptic device supplies the sense of touch. Additive, subtractive, and reformative techniques are supported by a compelling augmented reality display environment. In the PARIS augmented reality system the user's hands and the virtual images appear superimposed in the same volume so the user can see what he is doing. A haptic device supplies the sense of touch by applying forces to a handle or stylus that the medical modeler uses to form the implant.

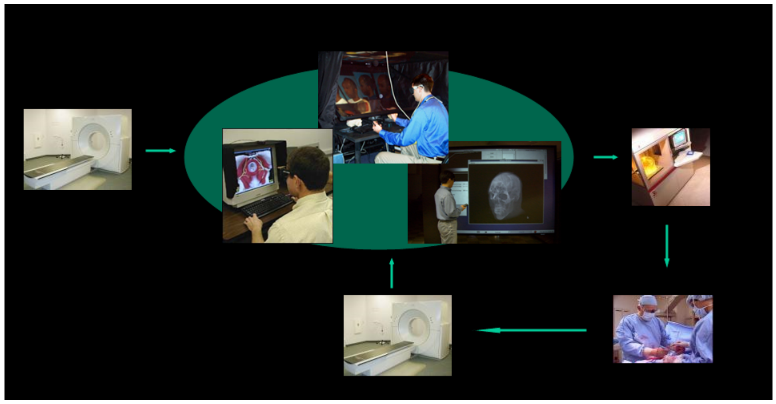

Figure 2: General approach.

After the virtual model of the implant is designed, the data is sent via network to a stereolithography rapid prototyping system that creates the physical implant model. After implant surgery, the patient undergoes a postoperative CT scan and results are evaluated and reviewed over the tele-immersive consultation system.

This system can be broken into several hardware and software components. These include an augmented reality implant modeling hardware system, modeling software, implant design, fabrication and testing, and tele-immersive surgical consultation. Each of these components will be discussed in the following sections.

3 Augmented Reality Immersive System

A virtual environment is designed to mimic the traditional working environment as closely as possible, providing more functionality for the users. For this purpose, the implant modeling augmented reality system includes stereo vision, viewer centered perspective, sense of touch, and collaboration. The Personal Augmented Reality Immersive System[5] developed at the Electronic Visualization Laboratory (EVL), University of Illinois at Chicago (UIC) has all these required features, and it is used in our study.

Augmented Reality combines the real world with computer generated images. In our study, it allows the modeler to see his/her own hands immersed in the computer generated models and virtual sculpting tools.

The PARIS system used in this study (Fig. 3) is an augmented reality device with a $5' \times 4'$ screen that uses a DLP projector to display three-dimensional (3D) stereo images with a 1400×1050 pixel resolution. A half-silvered mirror mounted at an angle in front of the modeler prevents the computer generated image from being blocked by the user's hands. This not only provides augmented reality but also avoids an important stereo vision depth perception conflict.

Figure 3: The Personal Augmented Reality Immersive System installed at the Virtual Reality in Medicine Lab (VRMedLab), UIC.

A tracking system with two sensors has been installed on the PARIS system. One of the sensors is mounted on a pair of LCD shutter glasses to track the movement of the viewer's head. The other is mounted inside a 3D interactive device, Wanda, to track the movement of the user's hand. The system can generate stereo images from the viewer's perspective and let the user interact with the data directly in 3D. A SensAble Technologies PHANTOM®desktop haptic device[6] is mounted on a desk in PARIS to provide sense of touch. This system combines virtual reality, augmented reality, and haptic reality. Fig. 4 shows a modeler is design an implant on the PARIS.

A Linux PC is used to drive the PARIS system. The PC controls two display devices at the same time; one is the projector on the PARIS, and the other is an ordinary monitor attached to the PARIS system. This second monitor is used to show the graphic user interface (GUI). With this dual-display configuration, we can separate the two-dimensional (2D) user interface (such as menus, buttons, dialogs, etc.) from the 3D working environment to avoid the complex, and often less effective, 3D user interface programming. The separation of the user interface and the sculpting working space allows much easier and smoother access to different functions of the application. This second monitor is configured as an independent X Window display. A touch panel screen is also an option as a device for the GUI on the PARIS System.

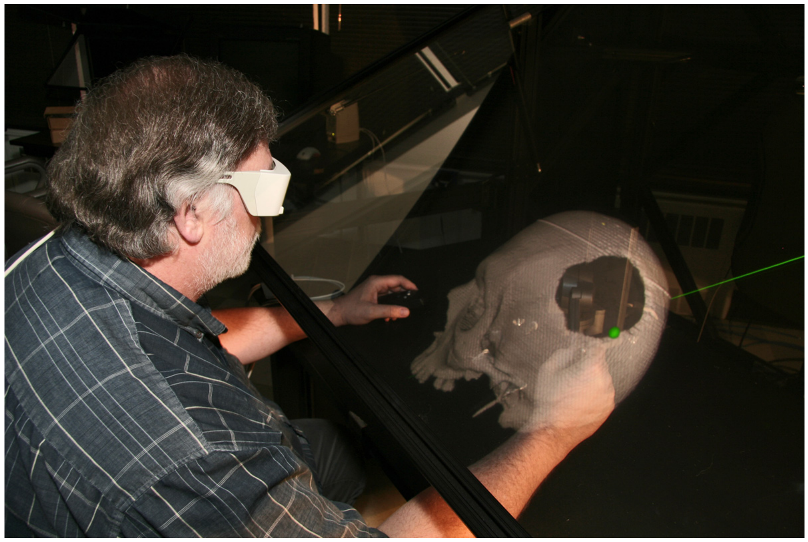

Figure 4: A modeler is building an implant on the PARIS.

4 Implant Modeling Software

Modeling software is needed for the creation of precisely fitting cranial implants. The specification and design of complex and arbitrary 3D shapes is very difficult. Shapes are best generated by sculpting procedures in 3D. Good visual feedback and the sense of touch are as crucial in virtual sculpting as in traditional physical sculpting.

We first developed a system to design cranial implants in a PARIS system useing surface modeling, and developed a preliminary sculpting componen.[7] Then a different approach, in which volumetric data is used directly, is generated. A direct volume rendering algorithm and a proxy-based force feedback algorithm have been developed for immersive implant modeling on volumetric data with haptics.

Computer algorithms and software tools were developed for volume rendering, haptic rendering, and sculpting.

4.1 Haptics Rendering Algorithm

The sense of touch is as crucial in virtual sculpting as it is in traditional physical sculpting. Modelers depend on tactile feedback while sculpting. Haptic devices have been used in virtual sculpting.[8, 9, 10]

There are two general approaches for direct volumetric haptic rendering. The first approach produces a force feedback from the data around the instrument tip and the velocity of the tip.[11] The second approach is a proxy-based algorithm[12].

A proxy-based algorithm has been used in haptic rendering of volumetric data.[12] Gradient was used to detect surfaces. The proxy used in the algorithm was a single point. While the point proxy worked well for volumetric data exploration, it is not suitable for sculpting purposes: the sculpting tool can easily go through a small gap.

A set of pre-calculated points on the surface of a tool has been used to calculate the forces.[13] The problem with this method is that if the tool is used for sculpting it will miss small particles when they are small enough to escape between the sample points.

A proxy-based algorithm can prevent the tool from penetrating the object, which is required when the modeler wants to navigate the surface of the object. We have developed a proxy-based haptic rendering algorithm that can be used directly on volumetric data for cranial implant design.[14] It is a proxy-based algorithm, and a spherical proxy is used to accurately calculate the force between the sculpting tool and the skull. The forces can be calculated according to the size of the tool and its relation to the data. Working together with a fast direct volume rendering algorithm using 3D texture mapping, a system for cranial implant modeling has been developed. The algorithm can also be used in volumetric data exploration.

4.1.1 Movement of the Proxy.

For virtual sculpting, the tool shouldn't be able to penetrate the object unless the sculpting option is activated. The algorithm we developed is based on the proxy-based approach, and a spherical proxy, which has the same shape as the tool, is used to remember the position of the tool.

While the tip is moving, the proxy follows in one of the two kinds of motions (Fig. 5). First, it moves straight to the tip point before it reaches the object (position A to position B in Fig. 5). If it reaches the surface of the object before it reaches the tip, a second motion starts: it moves on the surface of the object perpendicular to the surface normal (position B to position C in Fig. 5). The proxy stops moving when it reaches the tip, or when $\mathbf{f_s}$ is smaller than the friction.

When the proxy reaches a resting position, a force is generated to push the probing tool out of the object. Hooke's law is used to calculate the force, $\mathbf{F_h} = -k\mathbf{d}$, where $\mathbf{d}$ is the displacement of the tip of the haptic device from the proxy, and k is a parameter related to the material property.

Because of the discreteness of the volumetric data, it is not possible to calculate the surface normal precisely. Consequently it is difficult to keep the proxy moving precisely on the surface; it often travels into the object. To solve this problem, the proxy is pushed out of the object in the direction of the normal. This approach generates smooth motion.

Friction is also generated at the second stage. Without friction the object surface is slippery and difficult to handle when sculpting. The force on the proxy along the surface can be calculated, $\mathbf{f_s} = \mathbf{f} \cdot \sin\theta$, where θ is the angle between the force and the normal. Only when it is larger than the friction threshold,

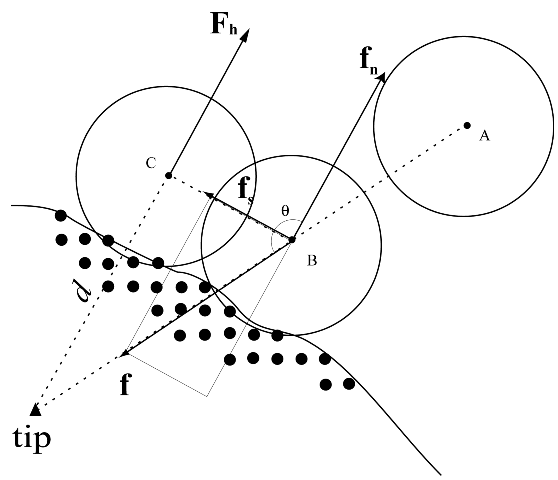

Figure 5: The proxy moves towards the tip either directly, if it doesn't touch the object (A $\rightarrow$ B), or along the object surface (B $\rightarrow$ C).

$\mathbf{f_t} = \mu\mathbf{f_n} = \mu\mathbf{f} \cdot \cos\theta$, the proxy is moving along the surface until the forces are balanced.

4.1.2 Force Calculation.

A spherical sculpting tool has been implemented. Instead of using pre-calculated sample points on the surface of the tool, all the voxels in the volumetric dataset which contact or fall inside the probing tool are used to calculate the elastic force (Fig. 6). It is problematic to use gradient as described in [12] to detect the surface for sculpting purposes. The tool may penetrate the surface, and the gradient can be noisy. Voxel value is used instead. The direction of the force from one voxel ($\mathbf{f_i}$) points towards the center of the spherical tool and is proportional to its distance to the surface of the probing spherical tool. The forces from all the voxels involved are summed together ($\mathbf{F}$) and the direction of the summed force is considered the same as the surface normal, which is used to calculate the direction of the proxy movement along the surface. With this method, the tool will not be able to squeeze through a narrow gap. The algorithm is accurate and the force feedback is realistic.

4.2 Sculpting Tools with Haptics

The sculpting software uses the haptic rendering algorithm we have developed to provide the sense of touch. Software tools that utilize haptics for the design, sculpting, and fabrication of high quality cranial implants are utilized in the augmented reality immersive system to create a virtual working environment for the modelers.[15] These tools use the haptic rendering algorithm directly on

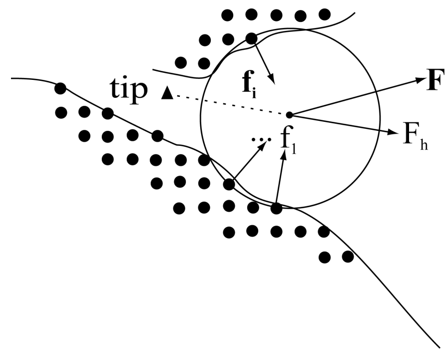

Figure 6: Force calculation.

patient CT data to provide a sense of touch. The patient CT data of a defective area is displayed in the implant modeling tele-immersive augmented reality system where the modeler can build a patient specific implant that precisely fits the defect.

The implant is designed by medical professionals in tele-immersive collaboration. Virtual clay is added in the virtual defect area on the CT data using the adding tool. A carving tool and a smoothing tool are then used to sculpt and refine the implant. These new haptic volumetric sculpting tools are a critical component of the comprehensive tele-immersive system.

A test cranial implant has been built using this system. The Visible Human Project® CT data[16] was used for this test. The CT data was segmented to remove soft tissue, and a simulated defect was created (Fig. 7(a)). To increase speed, the CT data was cropped to reduce the size of the data, only the defect and the surrounding part of the skull were kept (Fig. 7(b)). Virtual clay was added in a continuous stream in the virtual defect area using the toothpaste-like spherical adding tool (Fig. 7(c)). With force feedback the modeler can feel the edge of the defect and fill only the space where no bone is present. The gray-scale value of the sculpting material can be adjusted so that the implant is differentiated from the skull. The force feedback threshold can also be adjusted so that when adding clay the newly added clay will not interfere with the tool, but the user can still feel the edge of the defect. The virtual clay and the skull have different hardnesses. This allows the sculptor to touch the existing clay while adding new clay. When the defect was filled with clay (Fig. 7(d)), a carving tool was then used to sculpt the implant (Fig. 7(e)).

A surface refinement tool has been developed for volume sculpting. When the smoothing tool moved along the surface of the implant, the value of each voxel inside the spherical tool was recalculated. The new value was determined by averaging the voxels in a small neighboring volume. The designer can move the tool on rough surface areas of the implant, and the smoothing algorithm will be applied. Smoothness is limited only by the resolution of the volumetric data. The resulting implant together with the skull is shown in Fig. 7(f).

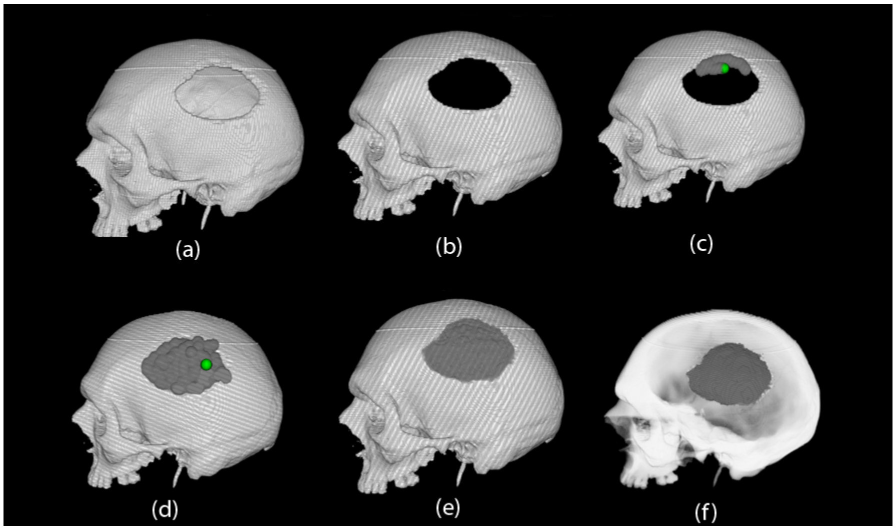

Figure 7: (a) A simulated defect using Visible Human Project® CT data. (b) The CT data was cropped and segmented. (c) Adding virtual clay. (d) Clay has filled the defect. A carving tool (green sphere) was used to sculpt the implant. (e) Implant material filling the defect. (f) The virtual skull with virtual implant after smoothing tool was used.

The last step in the design process is to push the implant out from the defect area. While it was pushed out, the software makes sure that any virtual clay in the path is removed. This trimming process makes sure that when the implant is put back in the defect area in the operating room, nothing will block the way. This edge trimming process is shown in Fig. 8.

The implant was then segmented (Fig. 9) and the marching cubes algorithm was used to convert the implant volume to a surface model. The surface model was converted to triangles and saved as a stereolithography (STL) model ready for fabrication.The STL model of the skull and implant were loaded into a computer program, and viewed with a cutting plane to analyze the fit (Fig. 10) and if no modifications are needed sent for stereolithography fabrication.

4.3 Direct Volume Rendering

The speed of the volume rendering is a very important issue in this application. Haptic rendering was carried out at a refresh rate of 1 kHz, but volume rendering was usually carried out at a much lower rate. The latency between the visual feedback and the haptic feedback lowers the quality of the immersive experience and effects the precision of the sculpting operation. Usually, 10 frames per second (fps) is considered real-time or interactive in computer graphics applications. Classically, 10 fps has been the minimum frame rate for real-time interaction. Classic animation was rendered at 12 fps. In this appli-

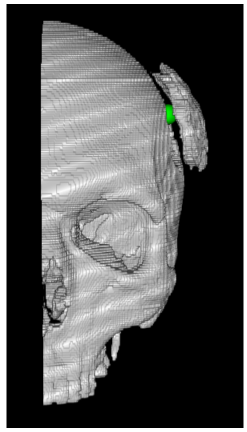

Figure 8: The implant is pushed out of the defect.

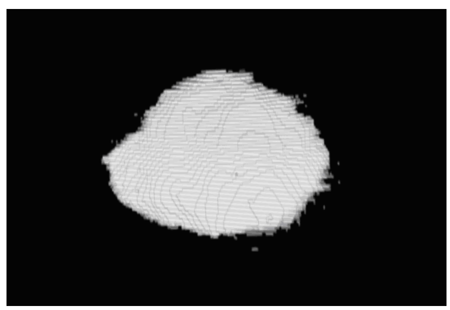

Figure 9: Smoothed implant segmented from skull.

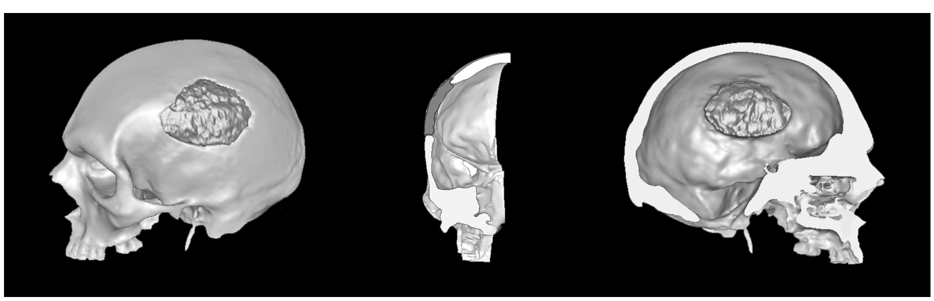

Figure 10: Implant fits in the defect.

cation, 20 fps is necessary to make the latency between the visual feedback and the haptic feedback unnoticeable. A fast volume rendering algorithm needs to be implemented.

The most commonly used volume rendering methods are: ray casting[17], 2D texture mapping[18], 3D texture mapping[19], and cluster-computing[20].

In this study a hardware assisted fast direct volume rendering algorithm has been developed using a commodity personal computer, Linux OS and a NVIDIA graphics card. 3D texture mapping features available in NVIDIA graphics cards were used to create an application that allows the user to view and interact with CT and MRI datasets. The algorithm supports multiple volumes. Gray scale volumes of the size of $512 \times 512 \times 256$ can be rendered on a 512×512 window in high quality at the rate about 20 fps. A level of detail technique was used to minimize the latency between visual and force feedback.

We have also developed ways to distribute volumetric information over the network in tele-immersive environments.[21, 22]

5 Implant Design

The implant design process uses patient CT data of a defective area. This volumetric data is displayed in an implant modeling tele-immersive augmented reality system where the modeler can build a patient specific implant that precisely fits the defect.

CT data of three patients with cranial defects has been imported to the implant design workstation. The implants were built in the tele-immersive system using the algorithms described in previous sections. Fig. 4 shows a researcher designing an implant using the augmented reality immersive system.

In order to test the fit of the implants designed using our implant design system, physical models of the patient data were built using the process of stereolithography. Implants were designed, fabricated, and tested for aesthetics and precise fit.

5.1 Case Studies

Three implants were designed in the PARIS environment using actual patient data. These tests take full advantage of the augmented reality immersive system.

5.1.1 Case 1.

Fig. 11 shows the patient's CT images with a large defect. The implant design process has been described in previous sections. This implant was designed on the PARIS system. The modeler can use the left hand to move and rotate the model with the help of a Wand, a 3D interactive device, while his/her right hand can sculpt the implant using a haptic device. The process in the virtual world is very similar to working on physical models. Fig. 12 shows the implant built with the system. Fig. 13 shows the implant together with the defect.

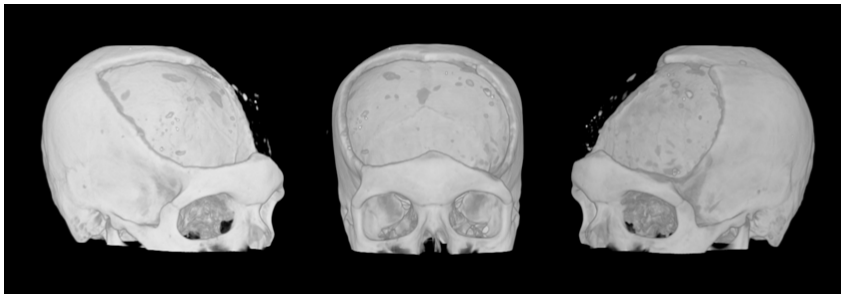

Figure 11: Case 1 - Patient's CT images from different angles.

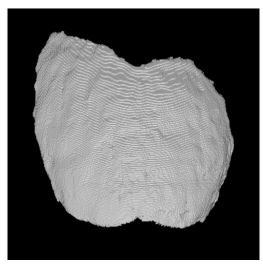

Figure 12: Case 1 - The implant.

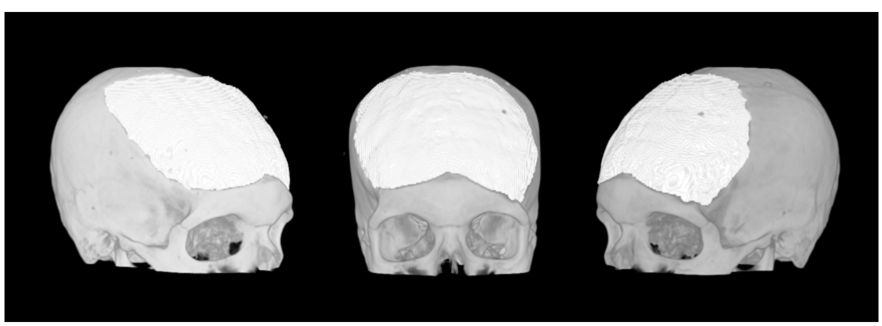

Figure 13: Case 1 - Implant with the defect.

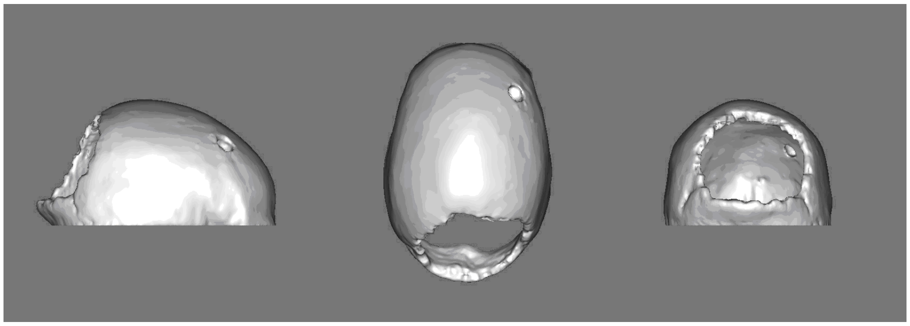

Figure 14: Case 2 - Data set of patient with large occipital defect.

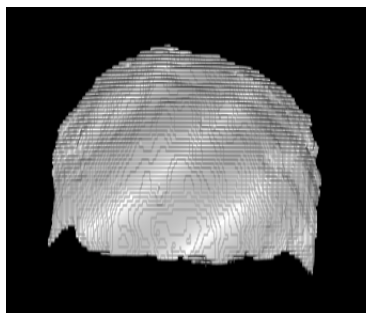

Figure 15: Case 2 - The implant.

5.1.2 Case 2.

Fig. 14 shows the patient's CT images with a large occipital defect in several different angles. Fig. 15 is the implant designed using the developed system. Fig. 16 shows that the implant fits well in the defect.

5.1.3 Case 3.

Fig. 17-19 show the implant design process for the third case with a large frontal defect.

The system can also be used for pre-operative planning, visualizing the results of the implant surgery before the operation actually takes place.

5.2 Implant Fabrication and Testing

To make a physical evaluation, the skull with simulated defect and the implant are fabricated via stereolithography to allow neurosurgeons to evaluate the quality of the implant.

All implants we built were also evaluated using commercial computer-aided design (CAD) software to test for fit before they were sent for stereolithography.

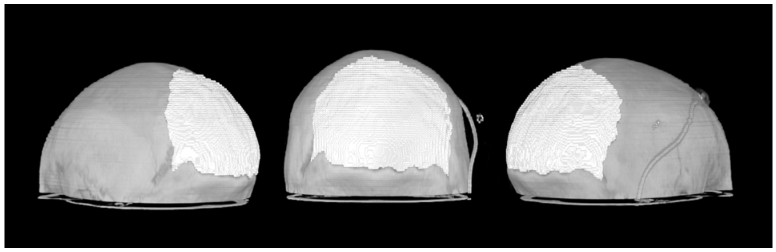

Figure 16: Case 2 - The implant with the defect.

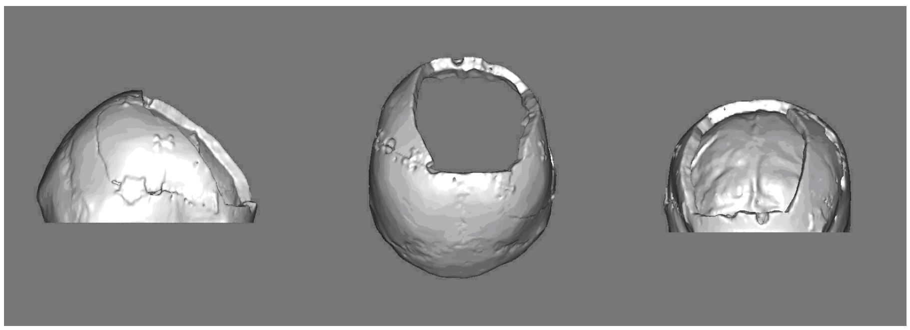

Figure 17: Case 3 - Data set of patient with large frontal defect.

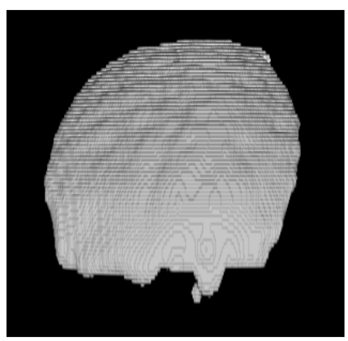

Figure 18: Case 3 - The implant.

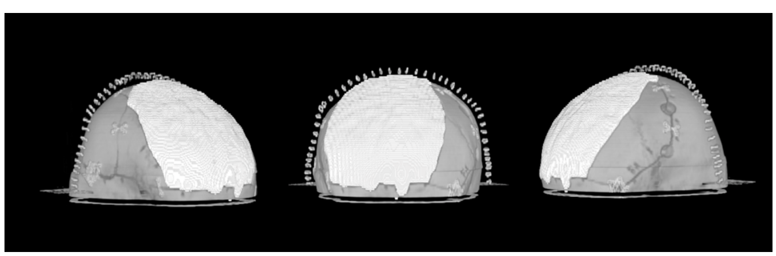

Figure 19: Case 3 - The implant with the defect.

Figure 20: Stereolithography fabricated skull with a simulated defect and the implant.

To allow neurosurgeons to make a physical evaluation for quality of fit and shape, the skull with simulated defect was fabricated via stereolithography (Fig. 20). The implant and the skull have been converted to STL format and fabricated to test the fit (Fig. 21). Fig. 22 shows the stereolithography skull model with implant in place. Tests demonstrate a very high quality fit.

6 Tele-Immersive Surgical Consultation

Based on the algorithms described in the last section, a tele-immersive system for cranial implant modeling has been developed. Three VR Systems are used in this networked environment: a Personal Augmented Reality Immersive System, a Configurable Wall (C-Wall), and a Physician's Personal VR Display (Fig. 23). Physicians and a medical modeler in different locations can work together in this tele-immersive environment. The PARIS system has been described in previous sections; other VR devices will be discussed in this section.

6.1 Physician's Personal VR Display

The recent development of small Linux personal computers and high-performance graphics cards has afforded opportunities to implement applications formerly run on graphics supercomputers. Affordable PC-based VR systems are comparable in performance with expensive graphics supercomputer based VR systems. Such VR systems can now be accessible to most physicians. The lower cost and smaller size of this system greatly expands the range of uses of VR technology in medicine. Using PC hardware and other affordable devices, a VR system has been developed which can sit on a physician's desktop or be installed in a conference room.

Because of the parallel processing of VR applications, a dual-processor hyper-threading Intel Xeon PC was used in this VR system. NVIDIA Quadro4 based graphics cards perform very well with our application software. Stereo glasses,

Figure 21: Stereolithography fabricated skull with a simulated defect and the implant.

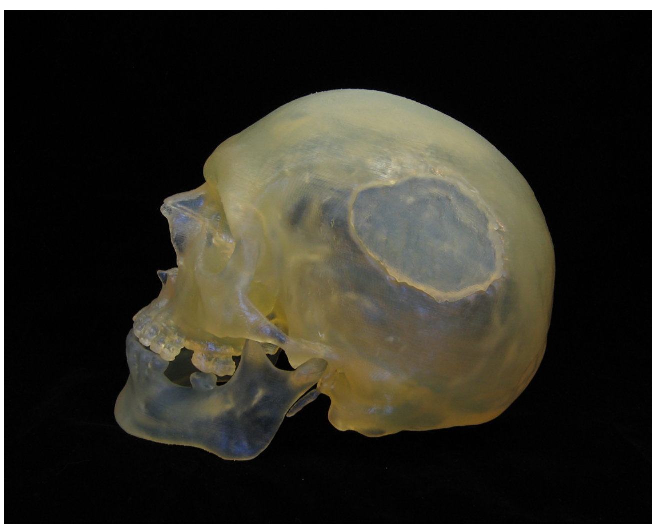

Figure 22: Stereolithography fabricated skull with implant in place.

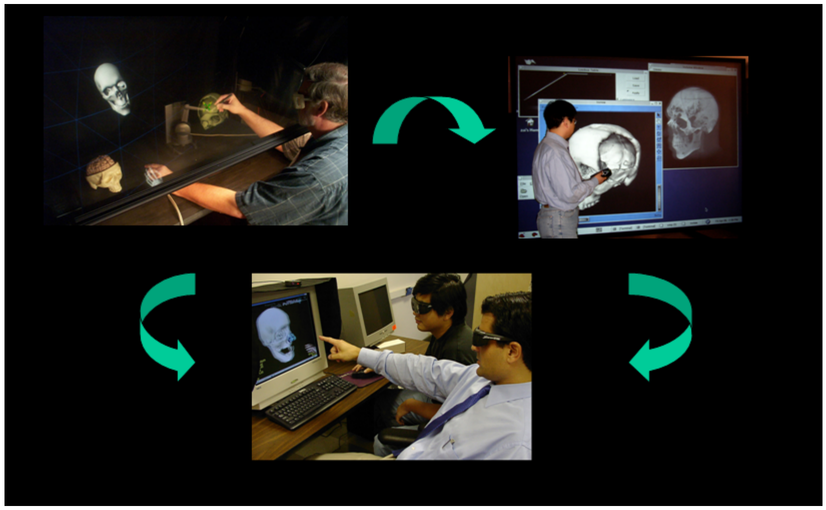

Figure 23: Tele-Immersive VR environment.

an emitter, and high quality CRT monitors were used to generate stereo vision for the desktop configuration.

We were using a standard PC mouse for user interaction and determined that it was not an intuitive interface for interacting with 3D data. We have now integrated a wireless presentation device, the "RemotePoint RF" made by Interlink Electronics[27].

6.2 Configurable Wall

A C-Wall is a tele-immersive display optimized for a conference room or small auditorium. There are many consultation contexts that work best with face-to-face communication and the C-Wall brings to this environment superior interactive visual display of medical data and the ability to interact over networks with collaborators in remote locations. The C-Wall utilizes two projectors and passive polarization to support stereo.

We have constructed a single screen, passive stereo C-Wall based on low-cost components for this project. We are using a PC identical to the PCs used for the Physician's Personal Desktop VR system. A dual-channel graphics card (NVIDIA Quadro4 980 XGL) is used in the PC to drive the projectors. Two identical DLP projectors (InFocus LP530 with 1024×768 resolution) are used to achieve polarized stereo, one for each eye's view. The stereo display uses circular polarizing filters for the two projectors and inexpensive circular polarized glasses. Different polarizing filters are placed in front of each projector lens, and then users wear polarizing glasses where each lens only admits the light from the corresponding projector.

We chose to use rear projection in our system so that viewers will not block the light from the projectors. A $72'' \times 96''$ rear projection screen has been set up. This screen can preserve the polarized light.

In order for the passive stereo to work, the images from the two separate projectors must match up on the screen. The two projectors are stacked on an adjustable stacker, but not exactly parallel to each other. By tilting one slightly, the two image areas on the screen overlap. The tilted projector's image suffers small keystone distortion in this case but the error is not significant, and is acceptable to users.

The NVIDIA Quadro4 graphics cards, which we use for both field sequential stereo (Physician's Personal Desktop System) and in twin view stereo (C-Wall) were swap buffering during active frame time. This resulted in a horizontal tear on the viewing screen. We were able to remove these undesirable effects by determining correct environment variables and NVIDIA GUI settings to force swap to vertical blanking.

6.3 Collaboration

Collaborative consultation and implant design is an important part of this project. Collaborative components have been added to the volume data manipulation program. The network component is implemented using the Quality of Service Adaptive Networking Toolkit (QUANTA)[28] developed at EVL.

QUANTA is a cross-platform adaptive networking toolkit for supporting Optiputer applications over optical networks. It consists of a collection of novel networking protocols that are designed for handling a wide variety of extremely high bandwidth application traffic flows; and a Quality of Service (QoS) architecture to flexibly control these protocols and support emerging wire and optical QoS mechanisms such as Generalized Multi Protocol Label/Lambda Switching (GMPLS). Quanta is a cross-platform adaptive networking toolkit for supporting the diverse networking requirements of latency-sensitive and bandwidth-intensive applications. It seeks to develop an easy-to-use system that will allow programmers to specify the data transfer characteristics of their application at a high level, and let Quanta transparently translate these requirements into appropriate networking decisions.

A tele-immersive collaborative VR server has been designed and set up in the VRMedLab, UIC. It has a database to store the shared data, such as CT or MR data. Collaborators' information is also stored in the database. Client applications can connect to the server to join existing collaborative sessions or open new sessions. Data is shared among collaborators. Real-time audio communication over the network is implemented among collaborators. It is implemented using the multicasting feature in QUANTA so that it can deliver real-time audio to an unlimited number of collaborators without the concern of bandwidth restrictions.

The network protocol for tele-immersive collaboration has been defined. Currently it contains the following parts: audio communication, state data sharing, and volumetric data sharing. All the participants in the collaborative session will share their viewing angle, transformation matrix, and sculpting tools information over the network. Any change made by any one participant will be transferred to all other participants. Any changes to the volumetric data will also be shared among collaborators

During collaborative implant design, the changes to the volume are shared in real-time among all participants. Only a sub-volume that contains the modified data is transferred to other collaborators in order to save bandwidth.

The implant design system is designed to run on different computer systems with different VR devices. The network component makes it possible for people using the application in different environments to share the data and interact with each other in real-time.

We tested tele-immersion on four systems at two different locations. At the VRMedLab, a PARIS system, a C-Wall, and a laptop PC were used for the testing. The tele-immersive server is also located at VRMedLab on a fourth computer. One and a half miles away on the other side of the campus, another PARIS system at EVL was used in the testing. Computers across the campus are connected over a campus network. The laptop PC was connected to the campus network via WiFi. Haptic devices are equipped on the PARIS systems.

During the testing, all four computer systems were connected to the server at the same time. When joining the tele-immersive VR session, the patient's CT data was transferred from the server to each computer, and displayed on their display devices. If any one of the users changes the view of the model, all others will see the changes in real-time. The PARIS systems equipped with haptic devices were used to build the implant collaboratively. And the sculpting process can be viewed on all the systems in real-time.

The tele-immersive session needs to be coordinated in order to prevent users on different systems from manipulating the model at the same time, which may cause some confusion.

The tests went very well. The networked system can be used for remote consultation and evaluation in VR environments as well as in a mobile environment.

7 Applications

The system is designed for tele-immersive implant modeling, it can also be used in many areas such as remote consultation, pre-operative planning, surgical simulation, post operative evaluation, education, and large-scale health emergencies.

8 Discussion

All implants fit very well, however if the resolution of the patient CT data is low, the fabricated implants are not smooth enough. The CT data can be interpolated, and implants can be built based on this higher-resolution data. Although optimum fit requires high resolution CT data, we believe this interpolated data can still yield relatively accurate results and can be used on patient with minimum modification in the operating room.

The time needed to calculate the force in the haptic rendering algorithm is related to the size of the tool and the density of the volumetric data. The overall performance of the force feedback algorithm is restricted by the CPU time available for force calculation, which was effected mainly by the time used for volume rendering. On a 2.80 GHz Intel Xeon dual-processor PC the algorithm works well on a $135 \times 395 \times 176$ volumetric data with 3596 voxels/cm^3 and the tool radius is 1.0 cm. When the tool size is increased to 1.5 cm, force instability may occur. The problem can easily be solved with a faster computer.

To generate stable force with the haptic device, the tool must rest at the position just contacting the object, otherwise a force step generated near the surface will cause vibrating and buzzing. It is possible that the proxy movement process oscillated and refused to reach the exit criteria, a counter was used to force it to exit the loop. It does not produce noticeable artifacts.

9 Conclusion

The Augmented Reality Immersive System has been designed and built to design patient-specific cranial implants. The software application has been developed to provide medical modelers a working environment mimicking the traditional workspace. It includes viewer centered perspective, 3D stereo vision, sense of touch, and augmented reality (the computer generated data lies in the same space as the user's hands). The system replaces the expensive and time consuming traditional sculpting steps such as physical sculpting, mold making, and defect stereolithography.

A proxy-based force feedback algorithm applied directly on volumetric data was created. The algorithm is accurate, and the force feedback from the volumetric data is calculated in real-time.

New volumetric tools were developed for the design and fabrication of high quality cranial implants from patient CT data. These virtual tools replace time consuming physical sculpting, mold making and casting steps. These new haptic volumetric sculpting tools are a critical component of the comprehensive tele-immersive system. An augmented reality system (PARIS) is used by a medical modeler to sculpt cranial implants. A conference-room-sized system (C-Wall) is used for tele-immersive small group consultation and an inexpensive, easily deployable networked desktop virtual reality system (the Physician's Personal VR Display) supports surgical consultation, evaluation and collaboration.

This augmented reality system is a comprehensive tele-immersive system that includes a conference-room-sized system for tele-immersive small group consultation and an inexpensive, easily deployable networked desktop virtual reality system for surgical consultation, evaluation and collaboration.

This system has been used to design patient-specific cranial implants with precise fit. It can also be used in consultation, pre-operative planning, implant design, surgical simulation, post operative evaluation, education, and large-scale health emergencies.

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