Project proposal: VR Guided Surgery – SDF Based Guidance and Safety

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1 Goal

Develop a Signed Distance Transform(SDF) based guidance and safety method for a VR guided surgery.

2 Team members, mentors

Team members: Juan Antonio Barragan and Hisashi Ishida
Mentors: Max Li, Adnan Munawar, Prof. Misha Kazhdan, Prof. Russell Taylor

3 Project relevance and significance

3.1 Medical Background

Mastoidectomy is a common procedure to treat an infection in mastoid air cells. The surgeon will cut the ear remove the hollow bone by drilling the temporal bone. This procedure can be highly challenging because it requires high precision to preserving the critical structures such as semicircular canals, sigmoid sinus, and facial nerves. Damaging those important structures can result in subsequent fatal complications, which vary from temporal or permanent loss of ringing in the ear or dizziness, partial or total loss of hearing, facial nerve palsy, or even death of the patients.

Figure 1: (Left) Mastoidectomy[1], (Right) Important structures concerned in the mastoidectomy[2]

3.2 Technical background

Previous work from Hopkins has developed a virtual simulator, AMBF(Fig.2), for volumetric drilling. This simulation leverages on segmented CT images to create an anatomically accurate drilling simulator environment which the users observe via a stereoscopic display. This simulator is particularly powerful because it allows users to practice surgical procedures while also generating data for surgical computer vision algorithms.

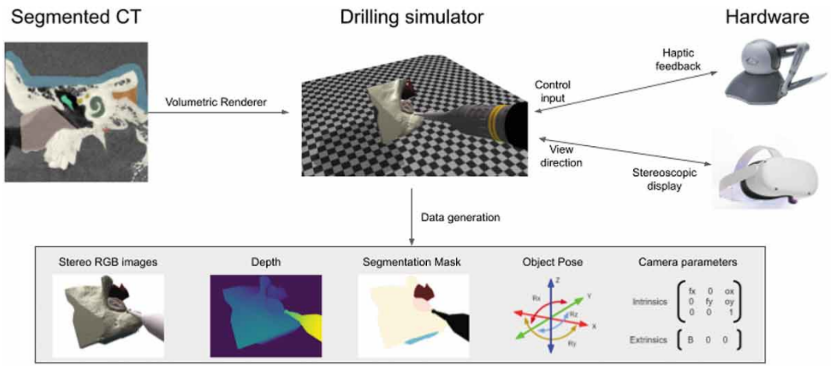


Figure 2: System Overview of AMBF[5]

Currently, the simulation environment does not provide safety cues related to the distance between the drill and critical anatomies. Although a warning message is provided when the user collides with an anatomy, this is not enough feedback to teach the train how to avoid such a dangerous situations in a real procedure. Secondly, the simulator lacks the capability of providing haptic feedback to secure the patient safety. We believe that improving these two aspects will result in improved safety for the patient and reduce workload of the surgeons.

3.3 Aim and Significance

- Aim 1: Implement SDF method for AMBF to monitor the distance between the tool and the static anatomy in real-time.
  - Significance: Provide fast and realtime monitoring method for all the anatomy and the tool.
- Aim 2: Propose SDF based feedback with different modalities
  - Significance: Provide additional safety for a VR guided surgery and reduce workload in the surgery.
- Aim 3: Expand our method to adapt SDF method for the time-varying volume
  - Significance: Provide useful guidance for drilling the temporal bone
- Aim 4: Write a conference paper
  - Significance: Share quantitative assessment results of our proposed SDF based feedback with the medical and engineering community

4 Technical summary

To improve the situational awareness and safety, it is necessary to calculate the distance between the drill tip and the anatomies in real-time. This information can be then utilize to prevent the user from drilling a critical anatomy or just to improve the user's awareness of close critical anatomical structures as he performs the procedure. This distance could be naively calculated by iterating over the voxel representation of the environment after each drill update. This however is a computationally inefficient algorithm that can result in high delays in the system.

As an alternative, signed distance fields (SDF) can be calculated for each of the anatomies in the simulation. A SDF function will generate a new voxel map in which the voxel's value is the minimum distance between that specific voxel location and the the reference anatomy. After obtaining a SDF for each of the different anatomies in the simulation, the calculation of the minimum distance between the drill tool tip and a specific anatomy can be speed up significantly. The procedure to obtain this distance would only require to query the SDF in the voxel where the drill is currently located. In this regard, SDF functions need to be calculated for all static anatomies at the beginning of the simulation to provided feedback to the user.

To achieved the goals of project, the work will be divided into three different phases each one with an unique and specific objective. Phase 1 will be focusing on integrating SDF functions into the drilling simulation for objects that do not change their volume. Phase 2 will be focusing on using the calculated SDF to improve the situational awareness of the user via haptic or visual feedback. The last phase of the project will be concerned with optimizing the calculation of SDF to perform them in real-time.

4.1 Phase 1

The goal for this phase is to implement SDF calculation functions for static objects whose volume is not changing over time, i.e., critical anatomies that are not being drilled on. For this phase, it will be assumed that the critical anatomies' SDF will be constant through out all the simulation, and therefore, the SDF calculation can be performed only once at initialization. Then, the calculated SDFs can be stored in a look-up table to be used while the user is interacting with the simulator. The diagram below summarizes the different components of the proposed system.

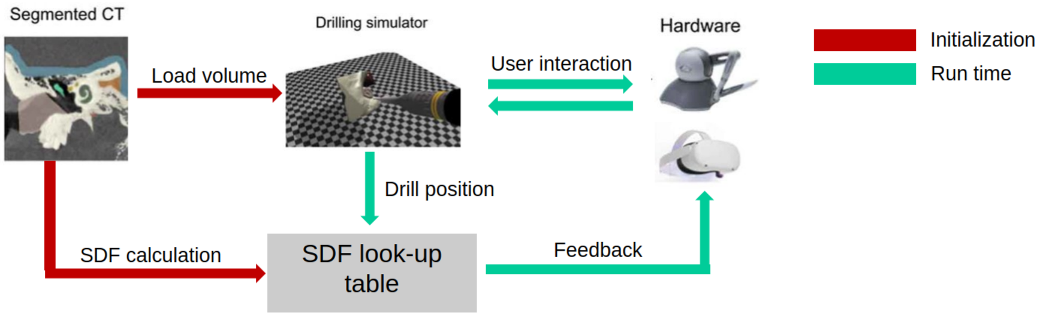


Figure 3: Phase 1 system architecture

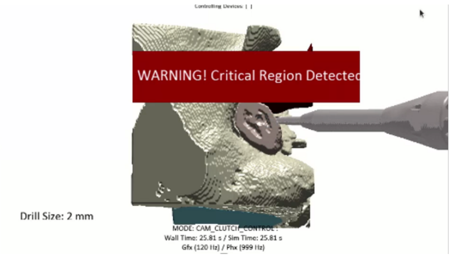
4.1.1 SDF calculation

The implementation of the SDF will be based on the method proposed by Saito and Toriwaki, 1994[6]. This method was chosen because it allows for parallelization of the calculations and works with volumes represented as voxel grids. These functions will be implemented in c++ and compiled as a shared library. Then, the library will be added to the simulation utilizing the AMBF plugins capability.

4.2 Phase 2

This phase aims to implement helpful feedback with different modalities for surgeons using the SDF look-table calculated in Phase 1. We are currently planning to implement two different feedbacks: visual warning and haptic feedback.

For visual warning, a warning message will be overlayed to the screen to provide an intuitive warning to the surgeons. This warning will be initialized when the drill passes a certain threshold using the SDF look-up table. Consequently, our method could provide situational awareness before damaging the important anatomy.



WARNING! Critical Region Detecte

MODE: CAM_CLUTCH_CONTROL
Wall Time: 25.81 s / Sim Time: 25.81 s
Gfx (120 Hz) / Phx (999 Hz)

Figure 4: Image of visual warning

For haptic feedback we are adopting the virtual fixture method, specifically the forbidden regional VF, to avoid collision with the anatomy using the gradient field of the SDF. Virtual fixtures are reported to be very effective in improving both the accuracy and the safety during the skull drilling experiment[4].

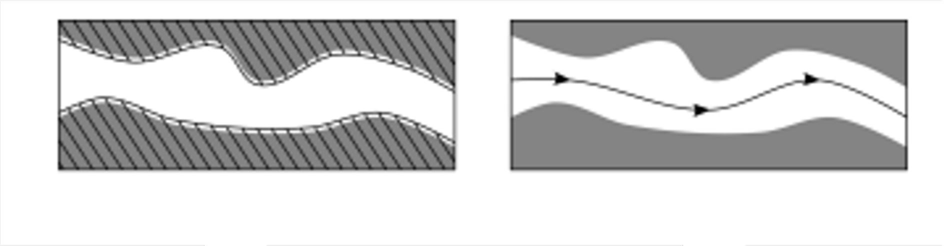
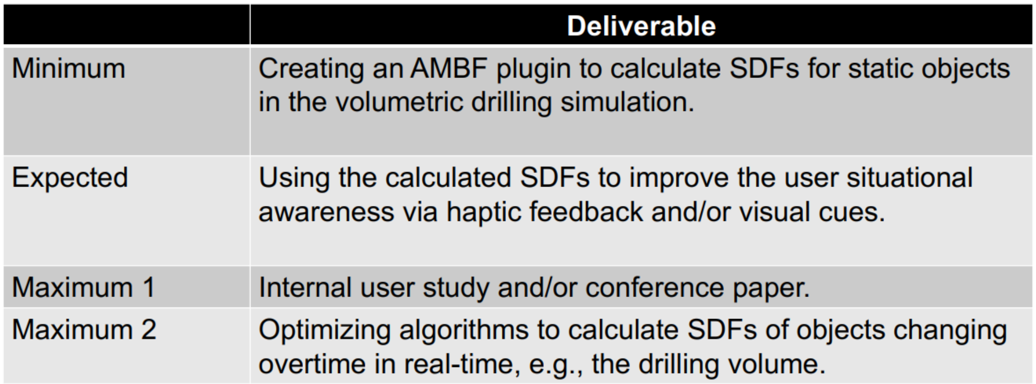


Figure 5: Concept of (Left)Forbidden regional virtual fixture and (right)Guidance virtual fixture[3]

4.3 Phase 3

Technical details of the phase 3, will be specified as soon as the phase 1 is finished. The reason for that is that the speed at which the SDF can be calculated is currently unknown. The speed at which SDFs can be calculated on the static case will determine the modifications required for real-time calculations.

5 Key Deliverables



	Deliverable
Minimum	Creating an AMBF plugin to calculate SDFs for static objects in the volumetric drilling simulation.
Expected	Using the calculated SDFs to improve the user situational awareness via haptic feedback and/or visual cues.
Maximum 1	Internal user study and/or conference paper.
Maximum 2	Optimizing algorithms to calculate SDFs of objects changing overtime in real-time, e.g., the drilling volume.

Figure 6: Key milestones of the project

6 Key dates & assigned responsibilities

Both Juan and Hisashi will take responsible for every tasks including the code implementation and data collections. The following is the list of the key dates.

- Project Approval(02/06/2022)
- Project Plan Presentation (02/22/2022)
- Project Plan Proposal Submission(03/01/2022)
- **Completion of Phase 1: Offline SDF calculation(03/16/2022)**
- Project Checkpoint(03/17/2022)
- Seminar Presentation (04/21/2022)

- **Completion of Phase 2: Situational awareness interface (04/27/2022)**
- **Completion of Phase 3: Online SDF calculation (05/05/2022)**
- Project Poster Session (05/??/2022)
- Project Final Report Submission (05/??/2022)
- Completion of Academic Paper (05/??/2022)

The Gantt chart for our project is as follows:

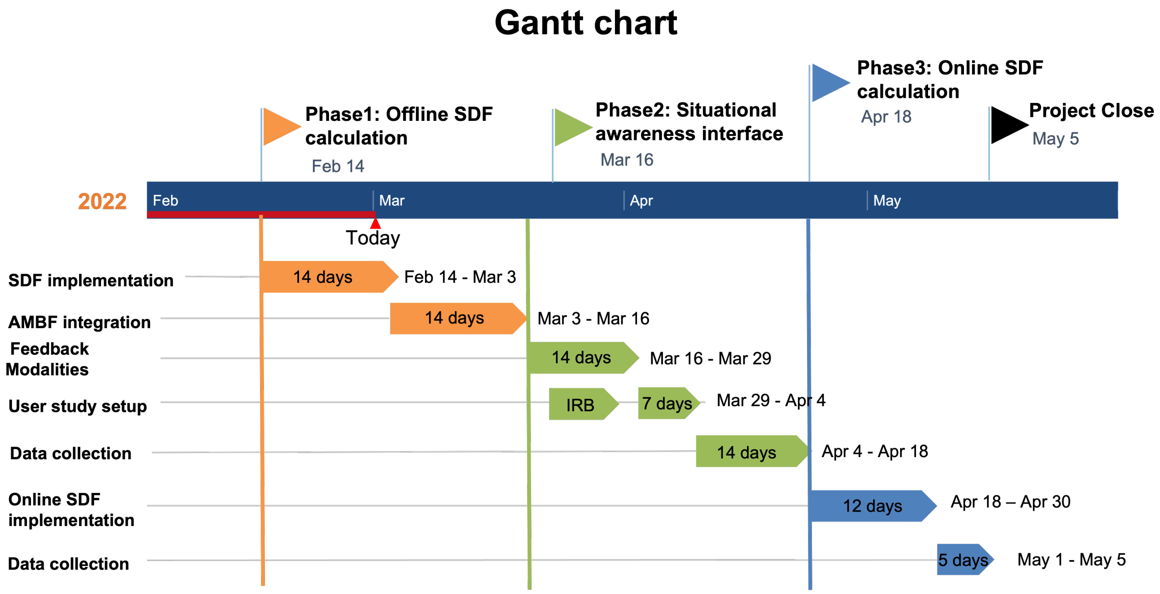
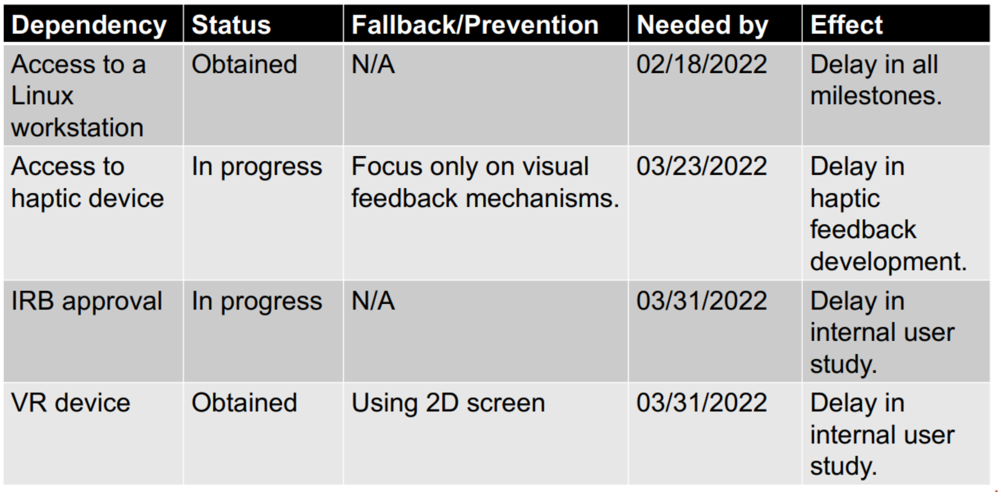


Figure 7: Gantt Chart of the project

7 List of dependencies

For project's first phase, the only required dependency is access to a linux workspace in which the simulator can be run. For the project's second phase, additional hardware will be required to develop the different feedback modalities. For the haptic modality a feedback device will be the main requirement. Additionally, for the proposed user study a VR device will be also required. In case of not acquiring any of those two additional hardware devices, the user study can be adapted to account for this fact.



Dependency	Status	Fallback/Prevention	Needed by	Effect
Access to a Linux workstation	Obtained	N/A	02/18/2022	Delay in all milestones.
Access to haptic device	In progress	Focus only on visual feedback mechanisms.	03/23/2022	Delay in haptic feedback development.
IRB approval	In progress	N/A	03/31/2022	Delay in internal user study.
VR device	Obtained	Using 2D screen	03/31/2022	Delay in internal user study.

Figure 8: Dependency table

8 Management plan

- Weekly meeting with mentors(Max Li, Adnan Munawar)
- Weekly lab meeting(Galen meeting with Prof.Taylor)
- Weekly team meeting
- Technical advisory meeting with Prof. Kazhdan and Prof. Taylor(on demand)
- Communication through Slack
- Code management with Github
- Additional file management with OneDrive

9 Reading list

1 A. Munawar et al., “Virtual reality for synergistic surgical training and data generation,” Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization, vol. 0, no. 0, pp. 1–9, Nov. 2021, doi: 10.1080/21681163.2021.1999331.

2 T. Saito and J.-I. Toriwaki, ”New algorithms for euclidean distance transformation of an n-dimensional digitized picture with applications,” Pattern Recognition, vol. 27, no. 11, pp. 1551–1565, Nov. 1994, doi: 10.1016/0031-3203(94)90133-3.

3 S. A. Bowyer, B. L. Davies and F. Rodriguez y Baena, ”Active Constraints/Virtual Fixtures: A Survey,” in IEEE Transactions on Robotics, vol. 30, no. 1, pp. 138-157, Feb. 2014, doi: 10.1109/TRO.2013.2283410.

4 Li, Z., Gordon, A., Looi, T., Drake, J., Forrest, C., & Taylor, R. H. (2020, October). Anatomical mesh-based virtual fixtures for surgical robots. In 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 3267-3273). IEEE.

References

[1] Mastoid surgery animation. https://www.youtube.com/watch?v=ZRxG_AmDaLI. Accessed: 2022-02-22.

[2] Tympanoplasty with cortical mastoidectomy? http://entsurgeonkemptonpark.co.za/tympanoplasty-cortical-mastoidectomy-2/. Accessed: 2022-02-22.

[3] Stuart A. Bowyer, Brian L. Davies, and Ferdinando Rodriguez y Baena. Active constraints/virtual fixtures: A survey. *IEEE Transactions on Robotics*, 30(1):138–157, Feb 2014.

[4] Zhaoshuo Li, Alex Gordon, Thomas Looi, James Drake, Christopher Forrest, and Russell H. Taylor. Anatomical mesh-based virtual fixtures for surgical robots*. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 3267–3273, Oct 2020.

[5] Adnan Munawar, Zhaoshuo Li, Punit Kunjam, Nimesh Nagururu, Andy S. Ding, Peter Kazanzides, Thomas Looi, Francis X. Creighton, Russell H. Taylor, and Mathias Unberath. Virtual reality for synergistic surgical training and data generation. 0(0):1–9. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/21681163.2021.1999331.

[6] Toyofumi Saito and Jun-Ichiro Toriwaki. New algorithms for euclidean distance transformation of an n-dimensional digitized picture with applications. 27(11):1551–1565.