Joint Resection Planning Agent for Robot-Assisted Laser Surgery

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Abstract

Knee arthroplasty or joint replacement has long served as the solution for conditions like osteoarthritis, providing relief from pain and immobility. However, traditional surgical methods employing mechanical cutting tools have their limitations, such as inaccurate bone resection and tissue damage. AIRO introduces a significant innovation, the HAiLO™ system, a robotic Laser Knee Surgery tool. Departing from the limitations of mechanical osteotomy seen in contemporary knee surgeries, the HAiLO™ system harnesses a robotically controlled laser, promising precision, reduced tissue damage, and enhanced implant fits. The Joint Resection Planning Agent (JRPA) plays a pivotal role in determining bone volume removal, implant, and bone fit analysis, and guiding ablation, aiming to amplify the system's efficiency and accuracy. This paper elaborates on JRPA's integral role in revolutionizing knee surgery through the HAiLO™ system, anticipating a transformative shift in medical technology and improved patient outcomes.

1. Introduction

Knee arthroplasty or joint replacement is a vital procedure for treating severe pain and immobility caused by conditions like osteoarthritis and rheumatoid arthritis. Traditional methods using mechanical tools have limitations, such as inaccurate bone resection and tissue damage (Beaty et al., 2020; Toksvig-Larsen & Ryd, 1991; Vaishya et al., 2013). To address these issues, AIRO is developing the HAiLO™ system, a state-of-the-art robotic laser surgery technique. A key component is the Joint Resection Planning Agent (JRPA), designed to enhance precision and efficiency in knee replacements.

Conventional knee replacement methods, while standard, have drawbacks like longer operation times and increased risk of complications. Given the high frequency of knee surgeries globally, improving these procedures is crucial for better patient outcomes and cost-efficiency. Current robotic methods still rely on mechanical tools, inheriting their limitations (Breuer, 2022). The HAiLO™ system aims to overcome these by using a robotically controlled laser for bone ablation, promising more accuracy, reduced tissue damage, and faster recovery. The prosthetics for the system are also designed to be lighter and more secure, decreasing the chances of implant failure (Honigmann et al., 2022; Khan, 2021).

The project's objectives focus on JRPA's role in determining the volume of bone to be removed, analyzing implant fits, and guiding robotic ablation. By meeting these goals, the HAiLO™ system is set to revolutionize medical technology and patient care.

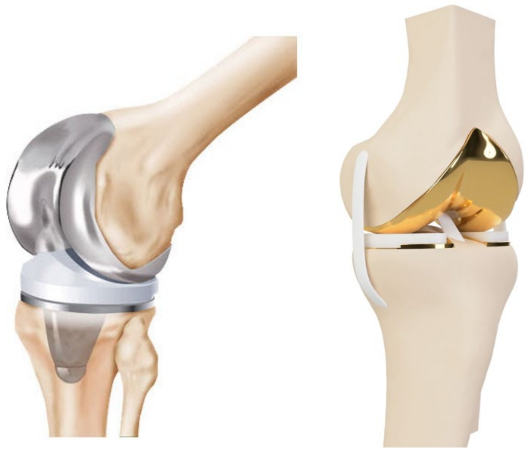

Figure 1 Post-Operation Renders of Total Knee Arthroplasty
Contemporary TKA – Left TKA with AIRO-x™ Implant– Right
(Surgical Watch, 2014)

2. Process

All code for the project was written in the Rust programming language. This choice was made as it is the language AIRO is using for most of their codebase. This will allow for easier future integration with AIRO’s software. Rust is an effective and safe language with strong guarantees for memory and thread safety.
To begin, a Graphical User Interface (GUI) application was developed. This provided a platform for visualizing progress and for ironing out complex three-dimensional mathematical problems. For visualization and editing of mesh objects, a mixture of my own GUI, mesh editing software such as MeshMixer and MeshLab, and CAD software such as Autodesk Inventor were used.

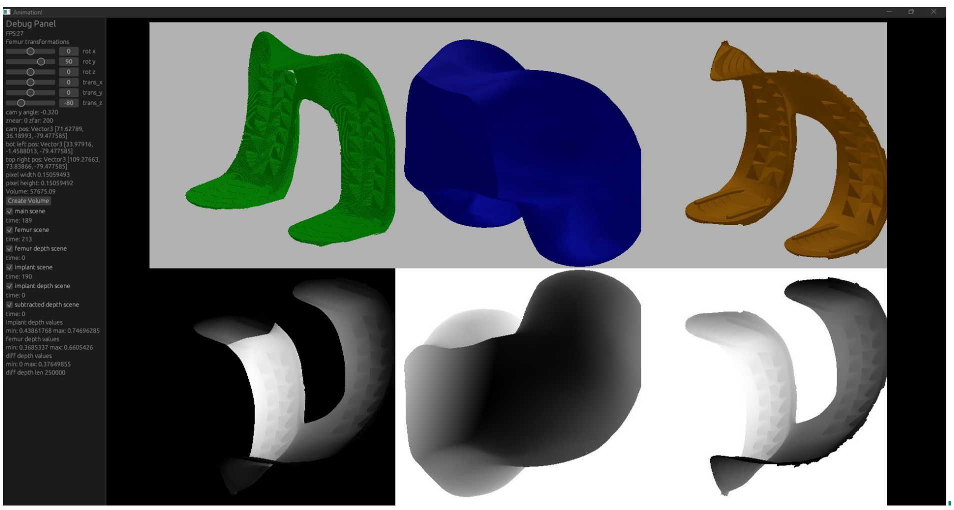

Figure 2 Custom Graphical User Interface for visualizing and debugging the JRPA, written in Rust.

2.1 Intersection Volume Analysis

To determine the volume of bone and other tissues to be removed, the intersection of the femur and implant needed to be determined. This intersection is the overlapping region of the two objects. Figure 3 shows the volume intersection of two cubes.

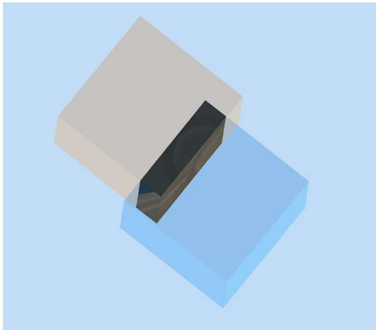

Figure 3 Two intersecting cubes; the intersection volume has been highlighted in black.

Calculating the volume and the intersection volume of two complex non-convex 3D objects is a complicated problem that is not trivial to solve (Günther et al.,1991). A range of methods were tried to calculate the intersecting volume.
CAD software can in most cases find and extract the intersecting volume of two objects. But for objects this complex the process was slow and most of these algorithms are proprietary, meaning they couldn't be used in a commercial project.

2.1.1 CPU Based Ray Intersection

Initially, a ray-based approach on the Central Processing Unit (CPU) was attempted for calculating the intersection volume of the implant. By 'firing' rays through the implant and femur and measuring where they hit, the new volume could be determined. This method was unfortunately sluggish, prompting us to harness the capabilities of the Graphics Processing Unit (GPU) instead.

2.1.2 VHACD Approximate Convex Decomposition

Measuring the volume of a non-convex object is difficult, but a convex object is easy. The VHACD algorithm was used to attempt to 'decompose' the implant and femur into multiple convex components (Mamou & Ghorbel, 2009). This algorithm seemed to struggle with the fine details of the implant and too much information was lost. Additionally, the convex object form of the implant made the next steps in the JRPA too difficult as well.

2.1.3 GPU Depth Buffering

The GPU's depth buffer functionality allowed for swift comparisons between two models, determining their differences. Rendering the objects and getting the depth buffer, then comparing gives a difference in height. This can be stitched back together into an intersection volume. The volume is a discrete approximation due to the nature of the depth buffer, but accuracy can be improved by rendering at a higher resolution at the cost of computation speed.

This method gave high speed volume analysis with good accuracy. To evaluate the accuracy of this method, cubes were utilized as test objects, as seen in Figure 3. For instance, the algorithm calculated a volume of 160.00658mm cubed for an actual cube volume of 160mm cubed.

In order to determine the volume of the femur bone that needs to be removed to accommodate the implant, the first step involved using a depth buffer approach. An example of the pipeline for this process is illustrated in Figure 2. The outcome was a comprehensive model that identifies the bone volume that should be excised for a precise fit of the implant, as shown in Figure 4

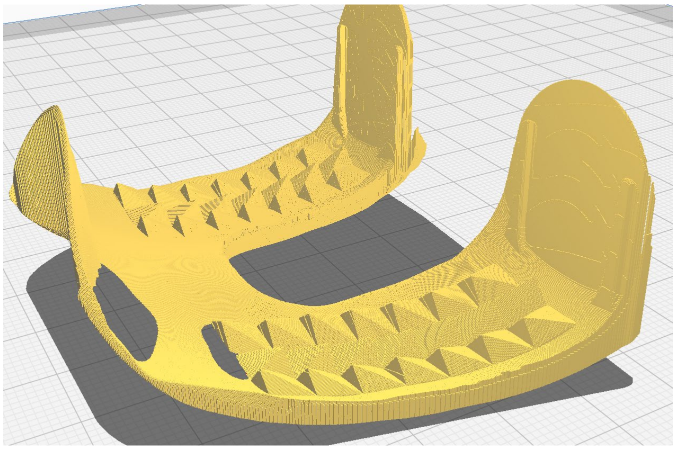

Figure 4 The intersection volume of implant and femur. This is the volume of bone that needs to be removed for the implant to fit.

Due to the discrete nature of the depth buffer, detail was lost in particularly the vertical section of the implant. For enhanced accuracy throughout the volume, distal, posterior, and anterior views were used and then restitched.

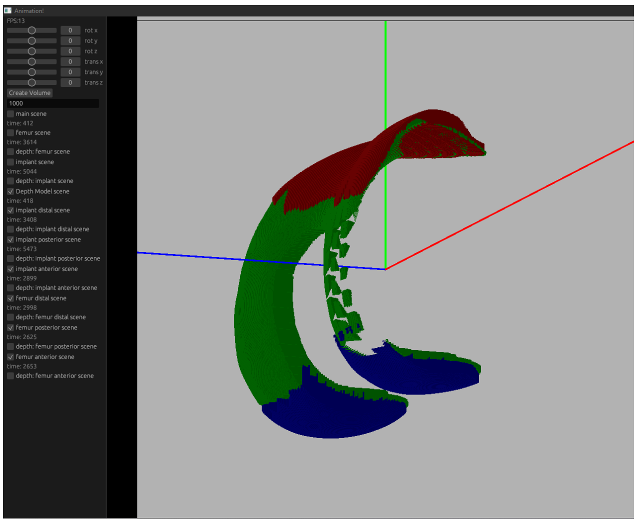

Figure 5 Intersection volume of implant and femur split into three distinct parts.

2.1.4 Point Cloud Analysis

Subsequently, a point cloud approach was also tested for volume intersection calculations. However, it proved to be less efficient and precise, as well as too computationally intensive for too little reward.

2.2 Ablation Simulation

The next stage involved simulating laser ablation. This helped in testing the next components of the JRPA without having to resort to lab testing. This also allows for the final fit of the implant to be determined in software.

2.2.1 Minkowski Sum for Bone Deformation Approximation

Due to the natural deformation and porosity of bone an exact bone cut to fit an implant will most likely result in a loose fit (Li et al., 2022). The ideal scenario is a small 'undercut' of the bone, allowing the bone to deform slightly to ensure the implant fits tightly and has good surface contact. To simulate this in a parametric and deterministic way a mathematical formula called the Minkowski sum was used. This under extrudes the surface of the implant so the bone is slightly undercut.

3. Results and Discussion

The program was equipped to handle both unilateral and total knee implants, ensuring a broad application scope. The volume analysis works well, for both unilateral and total knee volume analysis. An accurate intersection volume is obtained, which can then be used to plan the robot's movement paths and ablation runs. The process still relies on significant computation power and needs to be optimized more for speed.

The intersection volume can then be used to simulate the ablation of a bone, Figure 6 shows a simulated femur bone with a flat surface Laser-etched into it.

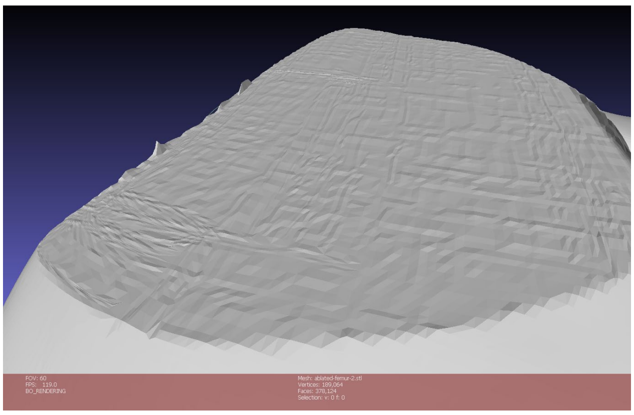

Figure 6 High-resolution femur surface after simulated Laser ablation.

4. Conclusions and Future Work

The existing data structure for intersection volume calculation is limited. Transitioning to an Octree-based structure could improve computational speed and solve issues in ablation simulation. The current laser ablation path, which works top-down, also necessitates further study to determine more efficient or anatomically feasible paths.

Post-ablation, the JRPA currently lacks the ability to evaluate bone surface characteristics such as roughness and implant fit. Adding these features in future iterations could improve implant success and longevity.

Finally, while this research focuses on the JRPA, its integration into the broader HAiLO™ system remains a significant future step.

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6. References

Beaty, J. H., Azar, F. M., & Canale, S. T. (2020). *Campbell's Operative Orthopaedics*. Elsevier.

Breuer, R. (2022). *Market Requirements* 2).

Goncalves, J. (2017). *Resection Surface Analysis Technical Report* (FRM-110:1).

Günther, O., & Wong, E. (1991). A dual approach to detect polyhedral intersections in arbitrary dimensions. *BIT*, *31*(1), 2-14. https://doi.org/10.1007/BF01952778

Honigmann, P., Hofer, M., Hirsch, S., Morawska, M., Müller-Gerbl, M., Thieringer, F. M., & Coppo, E. (2022). Cold ablation robot-guided laser osteotomy in hand, wrist and forearm surgery—A feasibility study. *The international journal of medical robotics + computer assisted surgery*, *18*(5), e2438-n/a. https://doi.org/10.1002/rcs.2438

Khan, R. J. K. F., Daniel Paul ; Robertson, William Brett ; Sheh, Raymond Ka-Man ; Ironside, Charles ; Chipper, Richard *Robot-assisted laser surgical system* (Australia Patent No. A. I. o. R. Orthopaedics.

Khan, R. J. K. F., Daniel Paul ; Robertson, William Brett ; Sheh, Raymond Ka-Man ; Ironside, Charles ; Chipper, Richard (2021). *An Orthopaedic Implant and a Surgical Orthopaedic System Incorporating Same*. A. I. o. R. Orthopaedics.

Mamou, K., & Ghorbel, F. (2009). A simple and efficient approach for 3D mesh approximate convex decomposition. *Proceedings of the International Conference on Image Processing.* Cairo: ICIP.

Li, C., Zhang, Z., Wang, G., Rong, C., Zhu, W., Lu, X., Liu, Y., & Zhang, H. (2022). Accuracies of bone resection, implant position, and limb alignment in robotic-arm-assisted total knee arthroplasty: a prospective single-centre study. *Journal of orthopaedic surgery and research*, *17*(1), 61-61. https://doi.org/10.1186/s13018-022-02957-1

Surgical Watch. (2014, 05 08). *Knee Replacements Overview*. Retrieved from Surgical Watch: https://surgicalwatch.com/knee-replacements/

Toksvig-Larsen, S., & Ryd, L. (1991). Surface flatness after bone cutting: A cadaver study of tibial condyles. *Acta orthopaedica*, *62*(1), 15-18. https://doi.org/10.3109/17453679108993084

Vaishya, R., Chauhan, M., & Vaish, A. (2013). Bone cement. *Journal of clinical orthopaedics and trauma*, *4*(4), 157-163. https://doi.org/10.1016/j.jcot.2013.11.005