Compact Surgical Navigation via Tool-Mounted Approach: Overcoming Line-of-Sight Limitations in Minimally Invasive Procedures

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Introduction

Image-guided surgery (IGS) has become increasingly popular for its applications in minimally-invasive surgery and interventional radiology. IGS is well established in neurosurgery, orthopedics, and otolaryngology, where navigation support gives surgeons improved understanding of the target anatomy and surrounding structures[1,2].

Optical tracking systems (OTSs) are one of the main standards for *in-situ* navigation and visualization[2]. Typically, a stereo near-infrared camera is placed above the surgical field to localize passive optical tools (Figure 1).

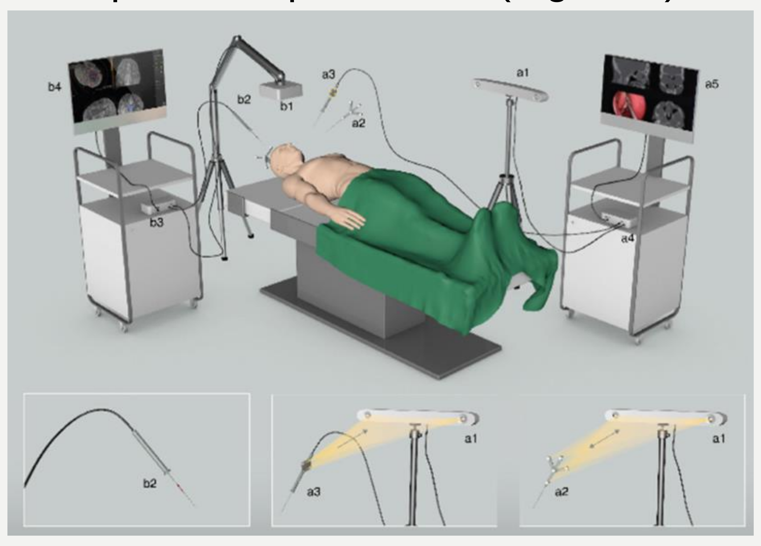

Figure 1. Typical OTS and electromagnetic tracking system setup[2].

However, conventional OTSs are often unable to track tools when even a single fiducial is obstructed, potentially lengthening procedure times and restricting surgeons' workspaces.

Objective: Reduce the line-of-sight issue by developing a tool-mounted OTS that tracks redundant fiducials surrounding an incision and maintains the sub-millimeter accuracy accepted in clinical settings.

Results

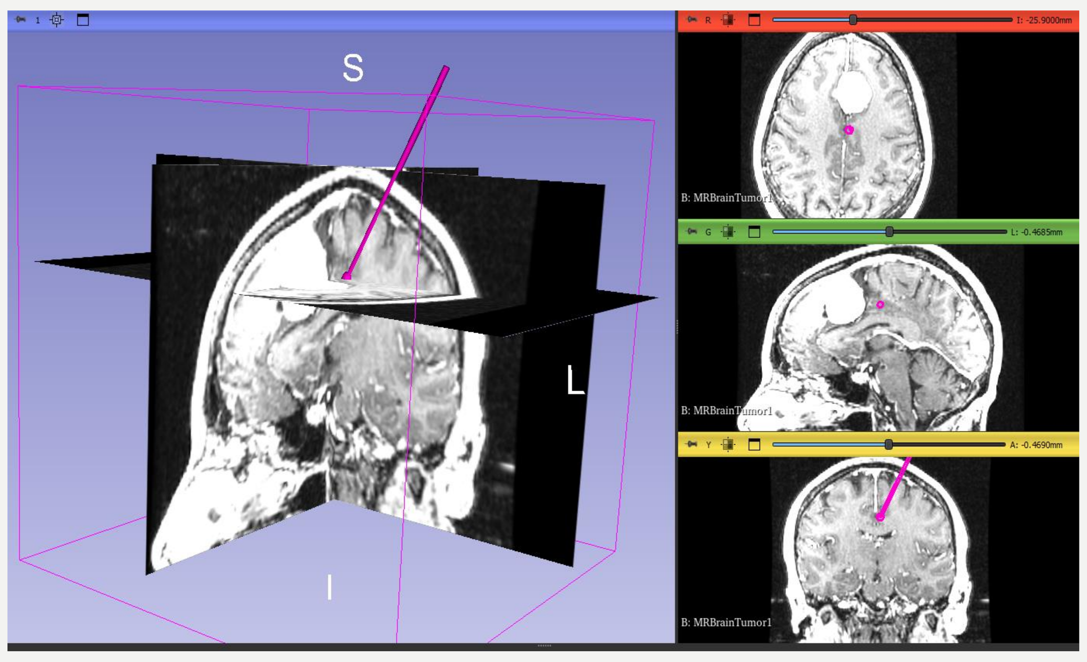

Figure 7. Visualization of tool tip pose driving resampling of preoperative MRI brain image in 3D Slicer.

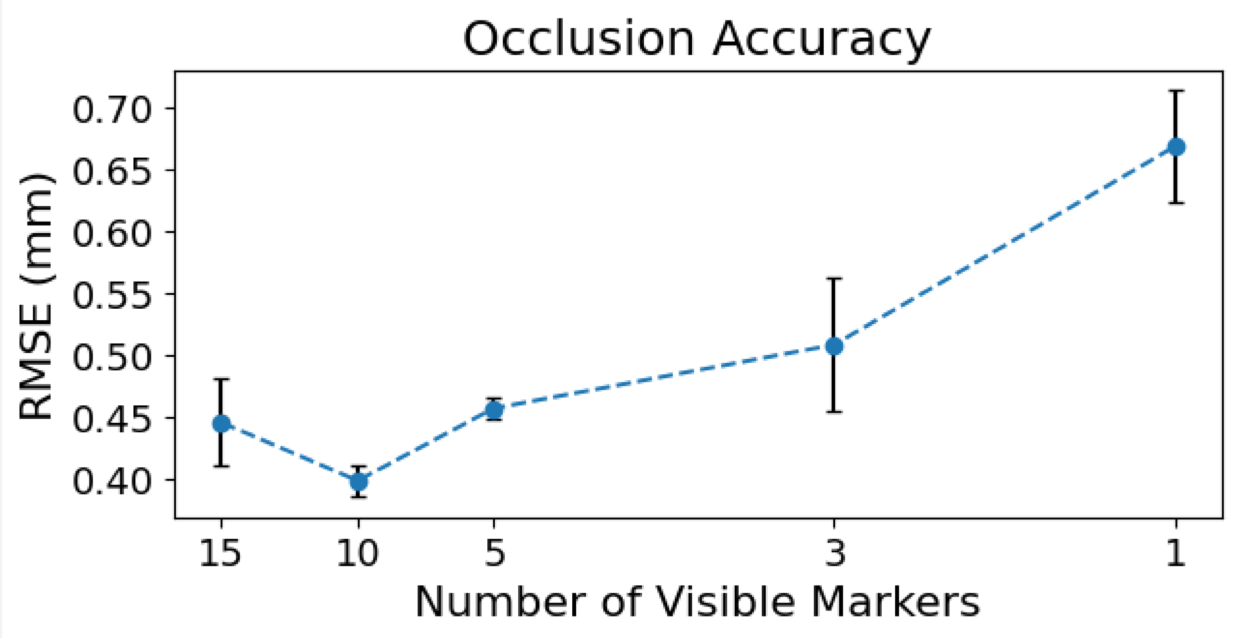

Figure 8. Root mean square error (RMSE) of Euclidean distance as number of occluded markers increases at (50, 50). For 10 markers, one side of the fiducial grid was occluded. For 5, two sides were occluded. For 3, only one side was visible. For 1, only 1 corner marker was visible. Recorded 10 times per variation. All figures display 95% confidence intervals.

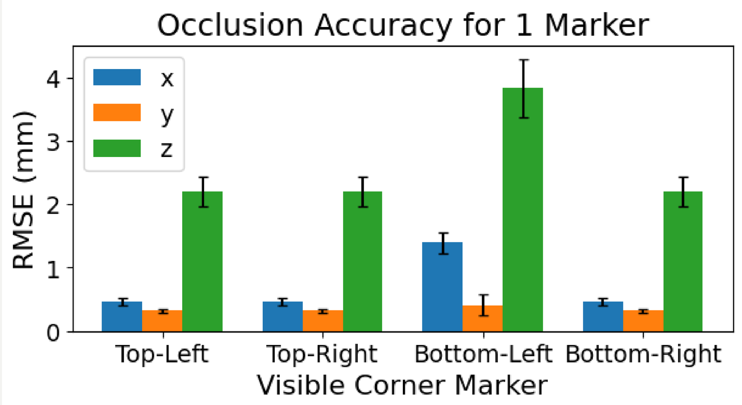

Figure 9. RMSE of each world axis at (50, 50) when 1 corner marker was visible. Recorded 10 times per corner.

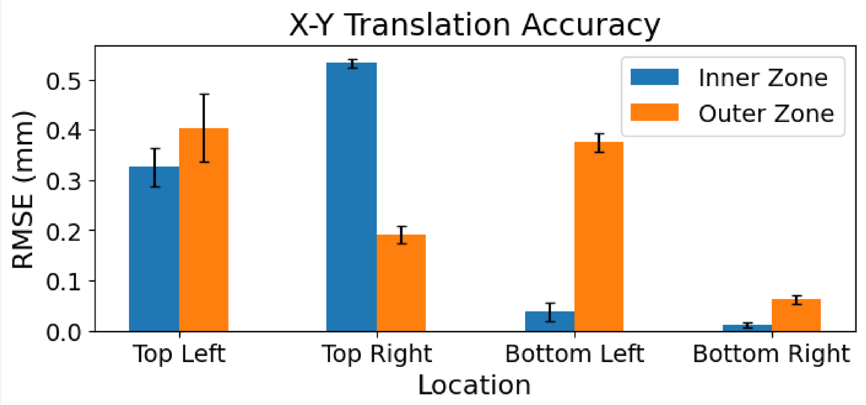

Figure 10. RMSE of Euclidean distance for Inner and Outer Zone positions. Recorded 5 times per variation.

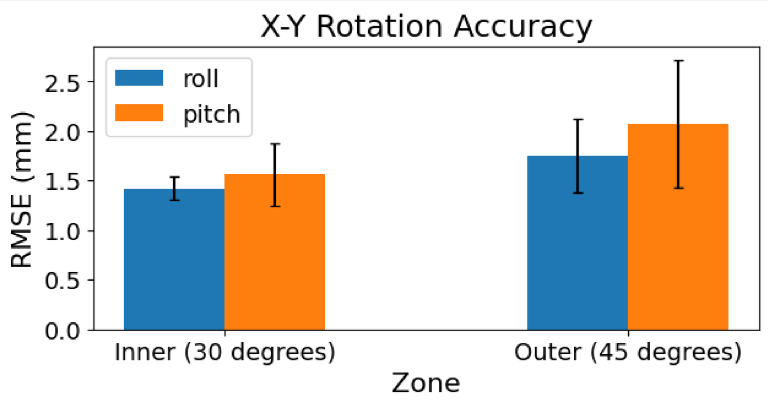

Figure 11. RMSE of Euclidean distance for Inner and Outer Zone angles. Recorded 5 times per variation.

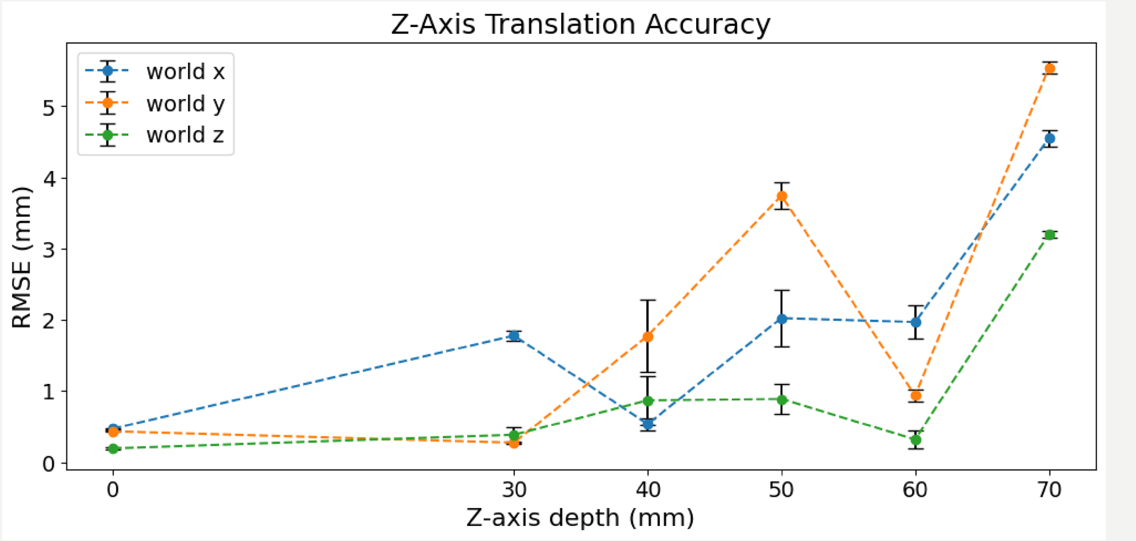

Figure 12. RMSE of each world axis as Z-axis depth increases at (75, 20). Recorded 5 times per depth.

Methodology

Logic

1. Tool-mounted setup eliminates need for separate camera systems
2. Use of redundant fiducials maintains accuracy even when several fiducials are obstructed by other tools and/or hands

Accuracy Evaluation Goals

- Occlusion Accuracy (Figure 8, Figure 9)
- X-Y Translation Accuracy in Two Zones (Figure 5, Figure 10)
- X-Y Rotation Accuracy in Two Zones (Figure 5, Figure 11)
- Z-Axis Translation Accuracy (Figure 12)
- Overall Accuracy in Reasonable Zone: Inner Zone up to 50 mm Z-Axis Depth (Figure 6)

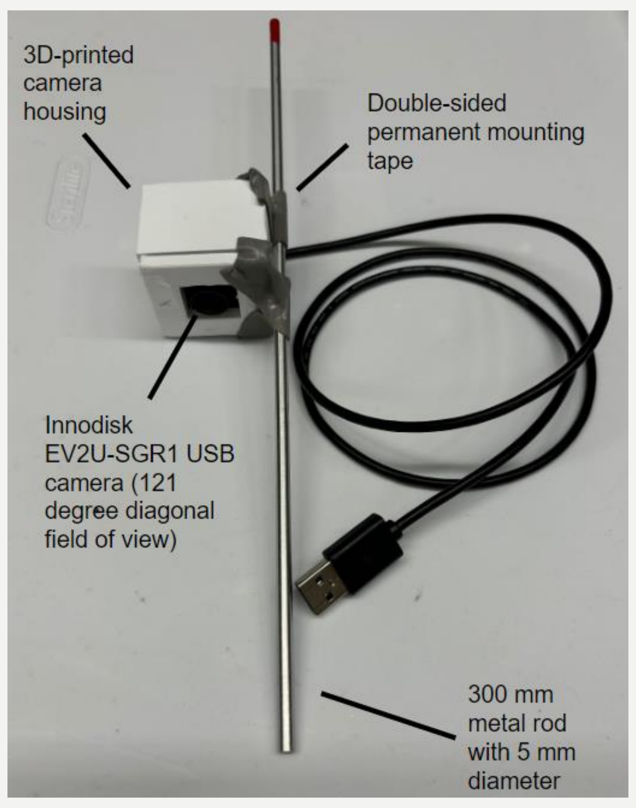

Figure 2. OTS components breakdown.

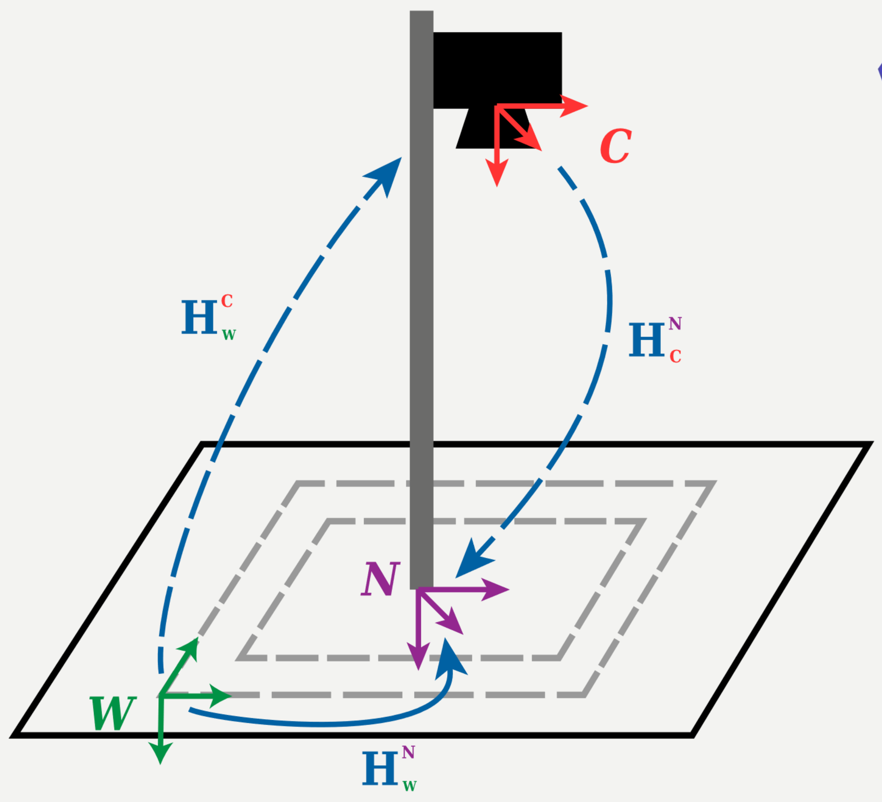

Figure 3. Homogeneous 4x4 transforms used to localize tool tip. Dashed arrows represent intermediate transforms. Dashed gray parallelograms represent fiducial grid.

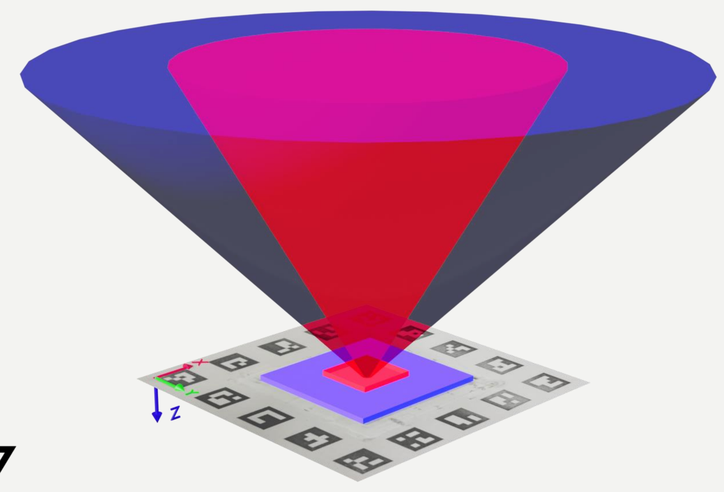

Figure 5. 3D rendering of Inner and Outer Zone volumes in red and blue respectively. World origin is also rendered. Depicts 100 mm x 100 mm fiducial grid marked with geometrically known coordinates. Inner Zone is defined as (40, 40), (60, 40), (40, 60), (60, 60) with maximum angle of 30 degrees. Outer Zone is defined as (25, 25), (75, 25), (25, 75), (75, 75) with maximum angle of 45 degrees.

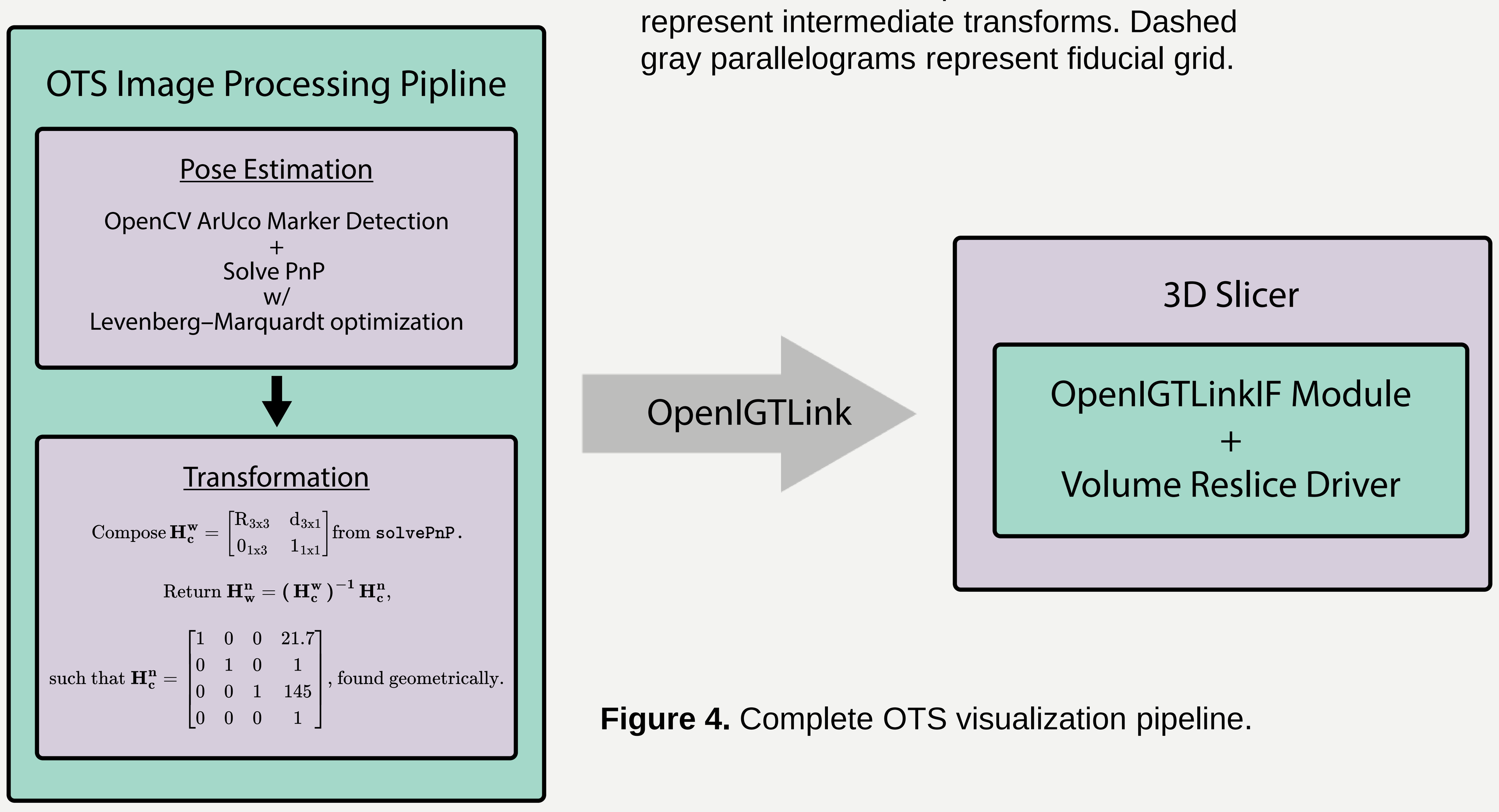

Figure 4. Complete OTS visualization pipeline.

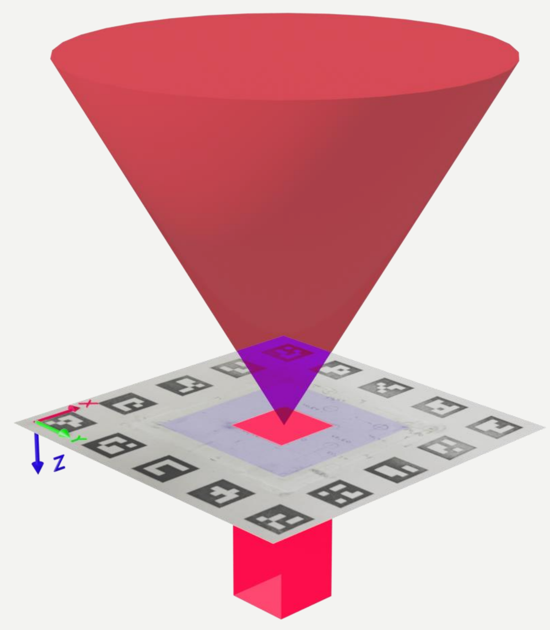

Figure 6. 3D rendering of Reasonable Zone volume and world origin.

Conclusions

Findings

- Overall **1.2 ± 0.1 mm RMSE** in Reasonable Zone
- Achieved millimeter to submillimeter accuracy even with many occluded fiducials
- Demonstrated integration of tool-mounted OTS into medical visualization platforms

Future Directions

- Improve stability of design
- Use pivot calibration to determine tip pose
- Evaluate OTS accuracy on phantom
- Incorporate embedded processing system and/or wireless receiver

References

1. B. Preim and C. Botha, "Chapter 18 - Image-Guided Surgery and Augmented Reality," in *Visual Computing for Medicine (Second Edition)*, Second Edition., B. Preim and C. Botha, Eds. Boston: Morgan Kaufmann, 2014, pp. 625–663.
2. A. Sorriento *et al.*, "Optical and Electromagnetic Tracking Systems for Biomedical Applications: A Critical Review on Potentialities and Limitations," *IEEE Reviews in Biomedical Engineering*, vol. 13, pp. 212–232, 2020.

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