Final Presentation:

SLAM based on the spotlight for retinal surgery

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Technische Universität München + Johns Hopkins Whiting School of Engineering

Introduction of robot-aided retinal surgery

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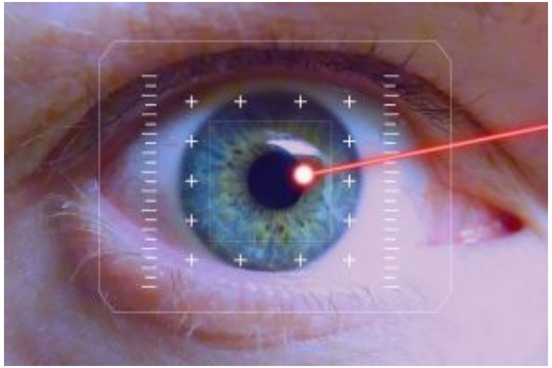
Retinal Surgery Challenges



High Requirements

- High Precision
- Controlled Movements
- Prevent accidental collisions

Many Limitations

- Unwanted Movements (patients)
- Hand tremor (surgeon)
- Bad visibility

→ Robot filter out hand tremors

→ Spotlight localizes the instrument

→ Mapping of retinal surface

Robot-assisted and Spotlight-based Retinal Surgery is of good significance.

Related work of localization of Spotlight for retinal surgery

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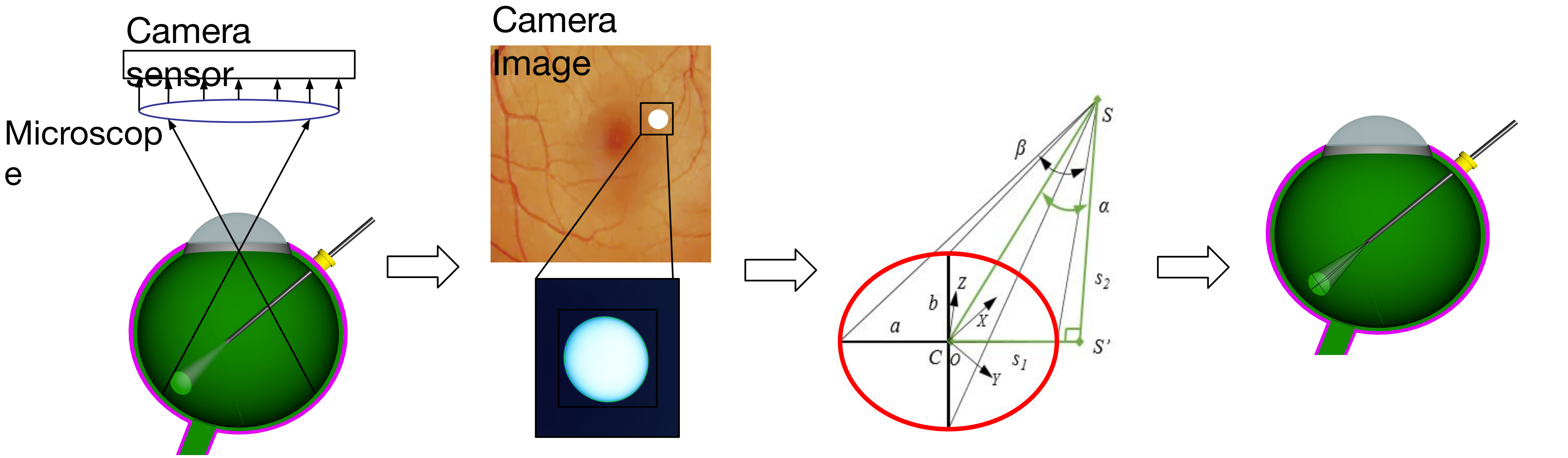
Spotlight-based Localization

Previous work: Workflow



Eye

Detected Contour

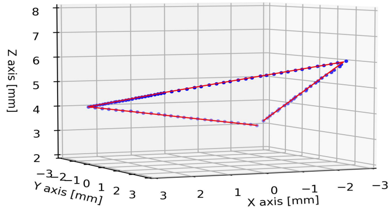
Reconstructed cone

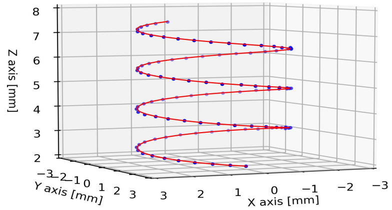
Position of instrument

Resource: Mingchuan Zhou , Felix Hennerkes,Nassir Navab"Theoretical Error Analysis of Spotlight-based Instrument Localization for Retinal Surgery" RAL-ICRA (2021).

Spotlight-based Localization

Previous work: Summary





Trajectories of spotlight in the simulation experiments: triangular and helix.

	Average Error [mm]	Maximum Error [mm]
Square (single)	0.026	0.100
Helix (single)	0.031	0.133

- \+ Good localization accuracy
- \- Lack mapping, which can guarantee the safety of eyeball
- **SLAMapping** ← What has been done in the research

Resource: Mingchuan Zhou , Felix Hennerkes,Nassir Navab"Theoretical Error Analysis of Spotlight-based Instrument Localization for Retinal Surgery" RAL-ICRA (2021).

Related work of mapping and retinal reconstruction

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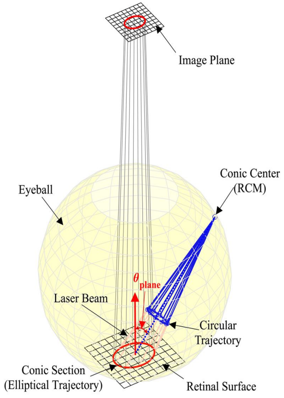
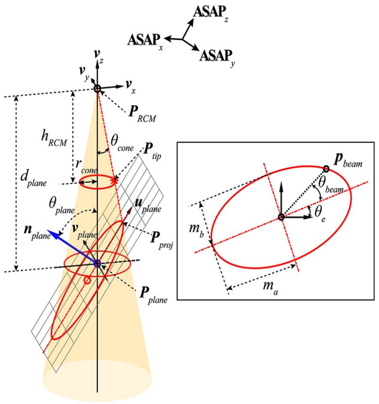
Retinal surface estimation using monocular vision

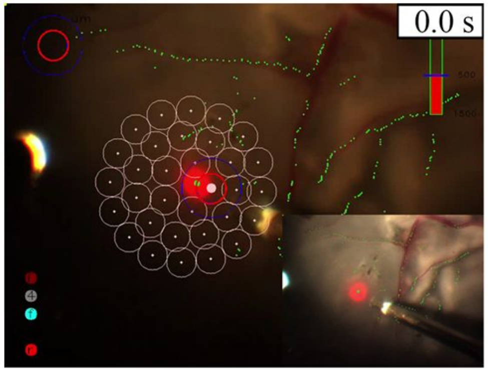
Plane Estimation using Projective Geometry



Conic section projects
on retinal surface



Cone beam analysis&
retinal surface estimation



Demonstration of intraocular laser surgery
on estimated retinal surface

Resource: S. Yang, J. N. Martel, L. A. Lobes Jr, and C. N. Riviere, “Techniques for robot-aided intraocular surgery using monocular vision,” The International journal of robotics research, vol. 37, no. 8, pp. 931–952, 2018.

Retinal surface estimation using monocular vision

Experiments: Summary

(a) (b) (c)

(a) Eye phantom filled with water and covered with a contact lens. (b) Dissected porcine eye placed inside the eye phantom without lens; (c) Intact porcine eye with cornea for ex-vivo test.

Experiment conditions	Mapping depth error [um]
Eye phantom test (wet)	>260
Open-sky test (dry)	>150

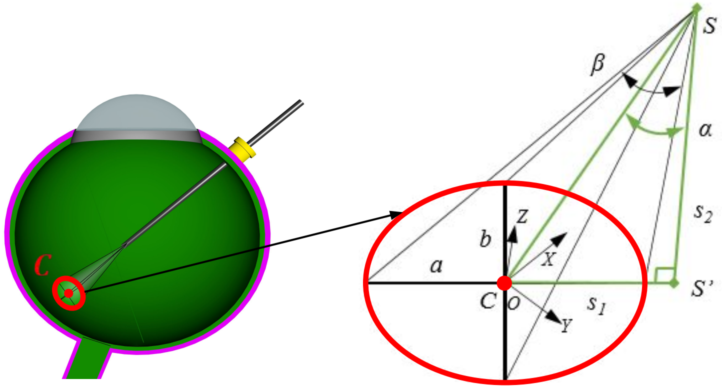
- + solid results in real experiments
- - accuracy of surface estimation alone is poor (>260um)
- - the estimated retina surface is actually a plane, far different from realistic

Resource: Mingchuan Zhou , Felix Hennerkes,Nassir Navab“Theoretical Error Analysis of Spotlight-based Instrument Localization for Retinal Surgery” RAL-ICRA (2021).

Concept of retinal surface mapping

Mapping: Transformation Method

Recap: forward computing the position of tool tip



Triangle (green) used to derive the vertex position based on a given ellipse. S denotes the spotlight source. C denotes center of ellipse, aka mapping point.

$$\left.\begin{aligned} C^w &= (x_c^w, y_c^w, z_c^w) \\ C^o &= (x_c^o, y_c^o, z_c^o) = (0,0,0) \\ S^w &= (x_s^w, y_s^w, z_s^w) \\ S^o &= (x_s^o, y_s^o, z_s^o) = f(\beta, \alpha, a, s_1, s_2) \\ \alpha &= sin^{-1}\left(\sqrt{1-\frac{b^2}{a^2}\cos(\beta)}\right) \\ s_2 &= a\left(\frac{\cos(2\alpha)}{\sin(2\beta)}+\frac{1}{\tan(2\beta)}\right) \\ s_1 &= a\frac{\sin(2\alpha)}{\sin(2\beta)} \end{aligned}\right\}$$

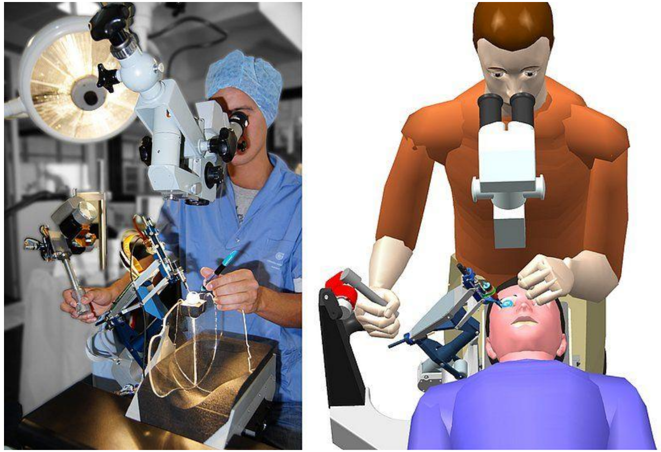
$$S^w = R_o^w \cdot S^o$$

R_o^w : transformation matrix

Resource: S. Yang, J. N. Martel, L. A. Lobes Jr, and C. N. Riviere, “Techniques for robot-aided intraocular surgery using monocular vision,” The International journal of robotics research, vol. 37, no. 8, pp. 931–952, 2018.

Mapping: Transformation Method

Reverse positioning the mapping points



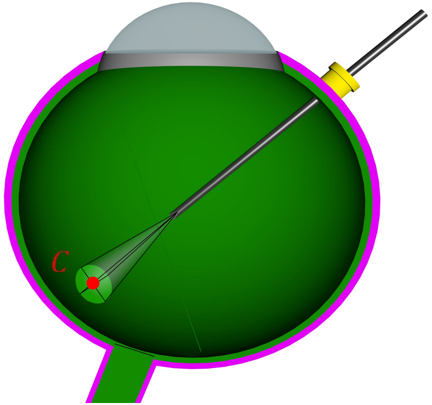
Optical surgery robot system (Preceyes BV)

Robot system provides the positions of the tip (S^w)
Cone reconstruction provides S^o

$$S^w = R_o^w \cdot S^o$$

$$R_o^w = (S^o)^{-1} \cdot S^w$$

$$C^w = R_o^w \cdot C^o$$

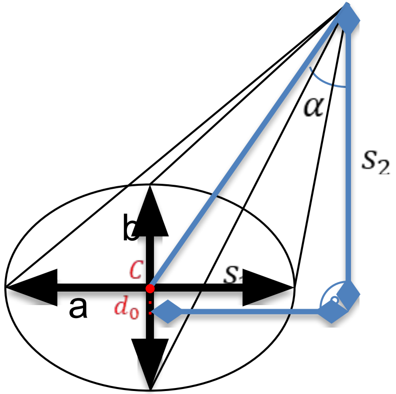


Mapping point: ellipse center on retinal

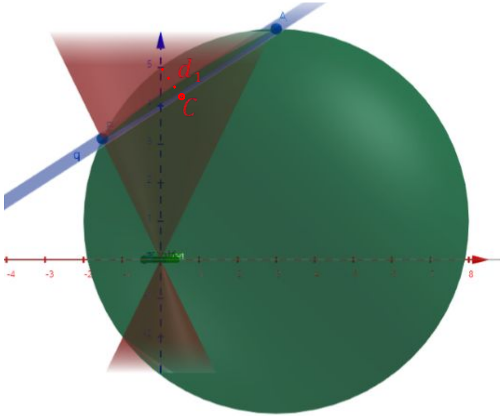
Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Mapping: Transformation Method

Errors analyze



d_0: distance between center of ellipse and real center of intersected 3D curve

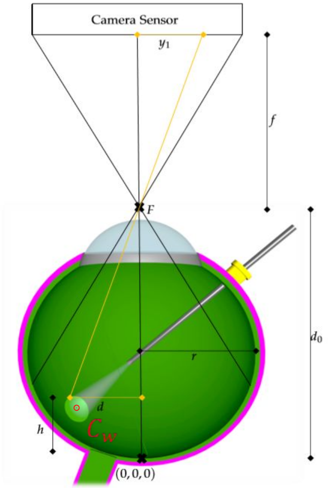


d_1: distance between ellipse plane and the retinal

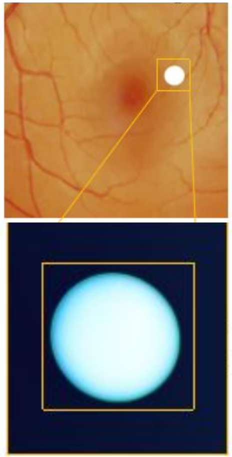
Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Mapping: Camera model Method

Pinhole camera model



Projection reconstruction



Contour detection

Contour gives points on image plane : (x_p, y_p)

y_1: *distance to center of image in pixel*

$$a = 1 + \frac{f^2}{y_1^2} \qquad b = \frac{-2\,d_0 f}{y_1} + \frac{2rf}{y_1} \qquad c = d_0^2 - 2d_0 r$$

$$d = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \qquad h = r - \sqrt{r^2 - d^2}$$

Back-project each point to global model: (x_r, y_r, z_r)

$$C_w = \left(\frac{x_{r,max} - x_{r,min}}{2}, \frac{y_{r,max} - y_{r,min}}{2}, \frac{z_{r,max} - z_{r,min}}{2}\right)$$

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Simulation experiment

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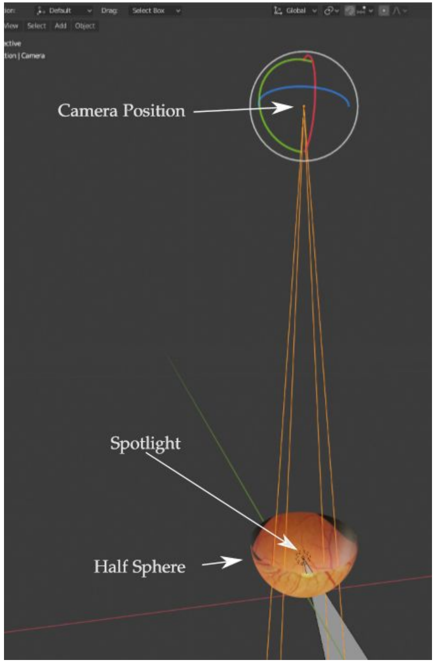
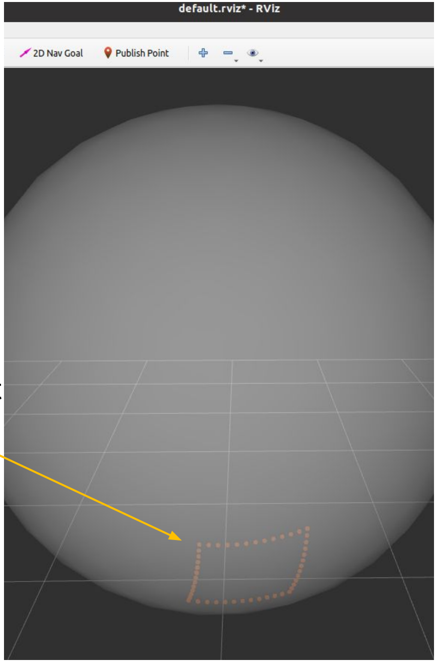
Blender & RGB completion



Setup in Blender

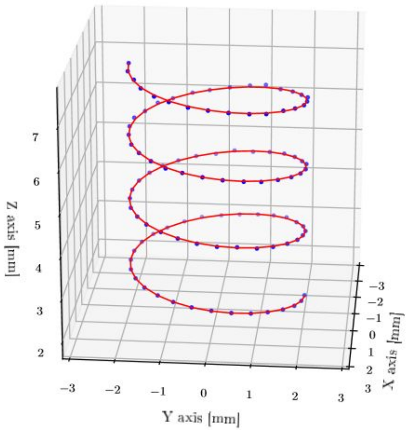
Captured image
(2048,2048)

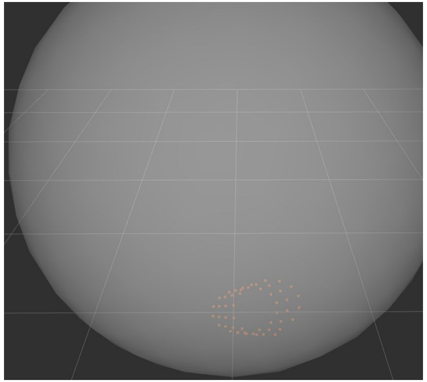


Eyeball in Rviz

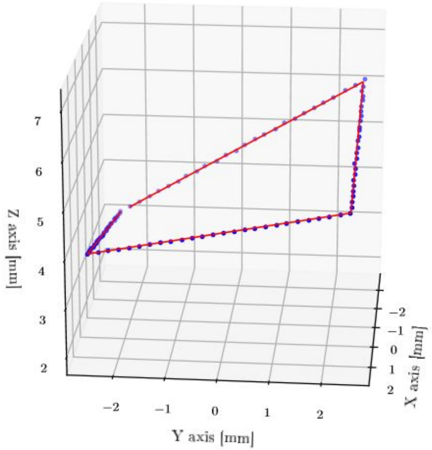
Trajectory selection

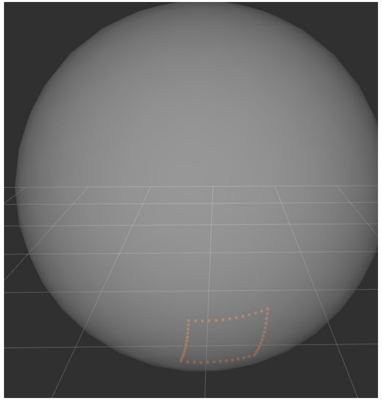
Previous trajectories





Helix



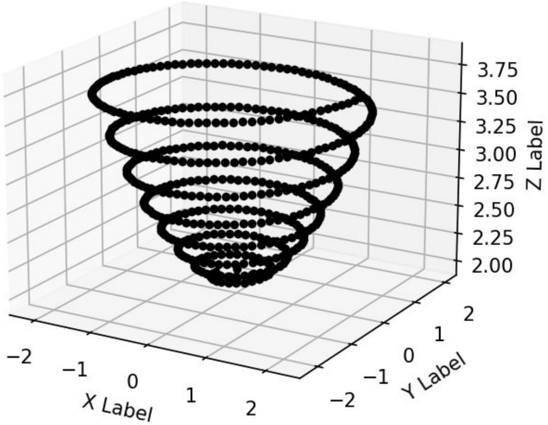


Square

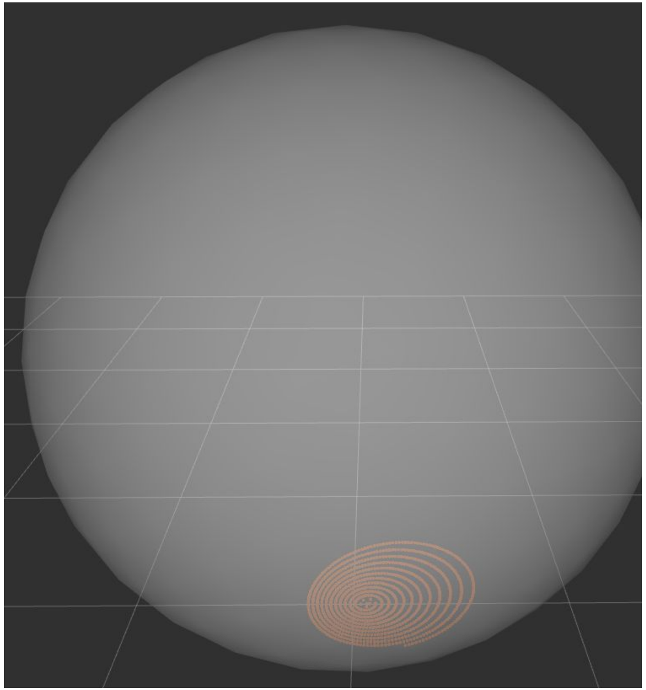
Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Trajectory selection

Archimedes spiral



Archimedes spiral

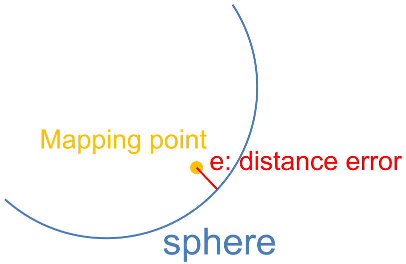


Mapping points in Rviz

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Results comparison

Evaluation metric and results



Evaluation metric

Mapping method / Trajectory	Mapping with transformation method	Mapping with reconstruction method
Helix	83	24
Square	82	18.5
Archimedes spiral	77	14.3

Distance error (in um)

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Deformed retinal surface

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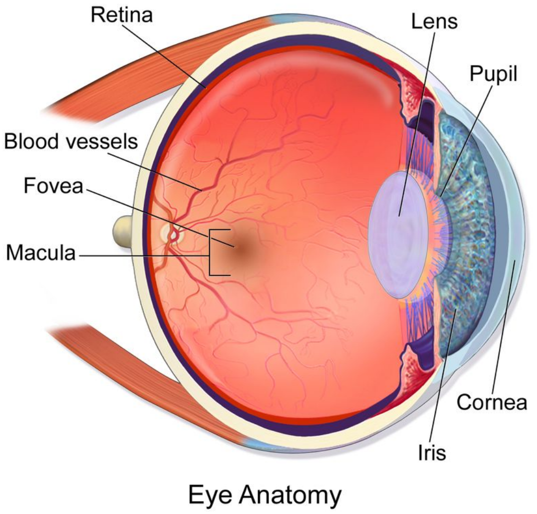
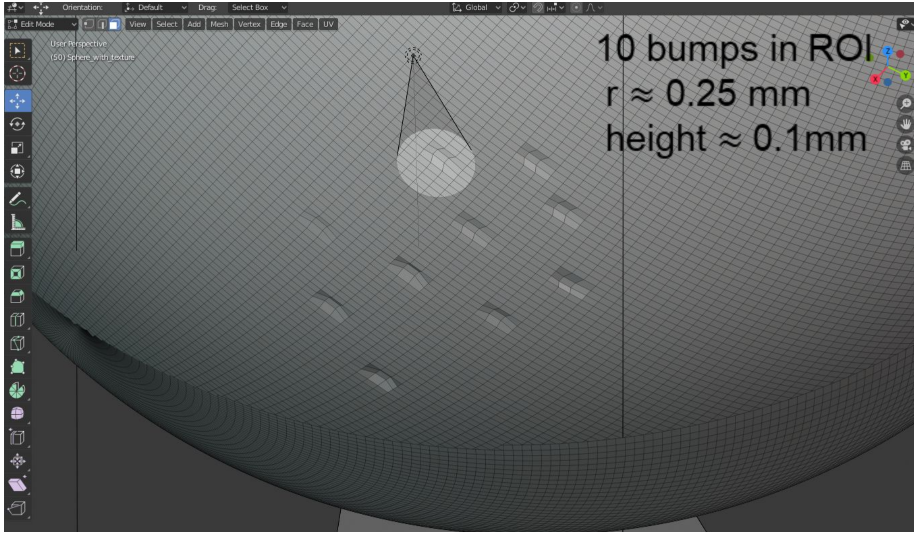
Deformed retinal surface





Retinal Macula

Add bumps on Blender

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Deformed retinal surface

Chamfer distance & sampling points

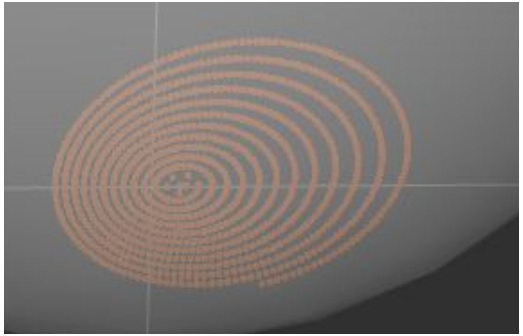
Chamfer distance:

S_1 *and* S_2 *are two points clouds.*

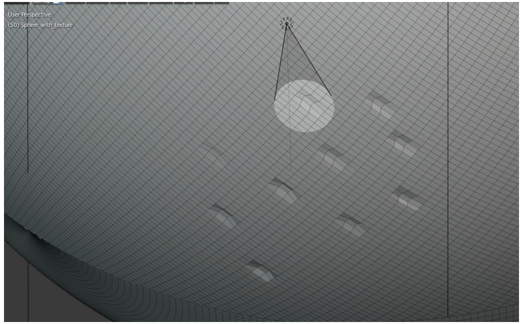
$$d_{CD}(S_1, S_2) = \frac{1}{S_1} \sum_{x \in S_1} \min_{y \in S_2} \|x - y\|_2^2$$

Sampling points:

Vertexes in Blender model.



Mapping points: S_1

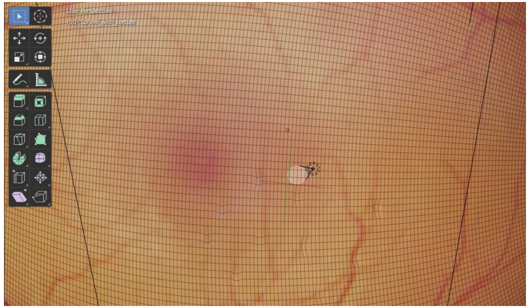


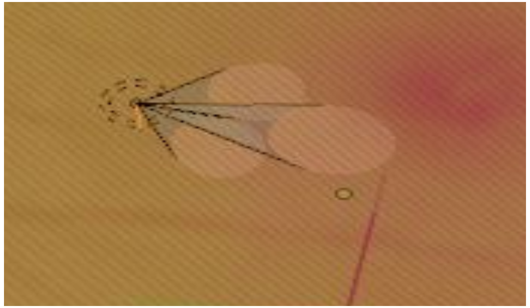
Sampling points on retinal: S_2

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Deformed retinal surface

Chamfer distance & Errors





Top: 30 k vertexes. Bottom: 2 Mio vertexes.

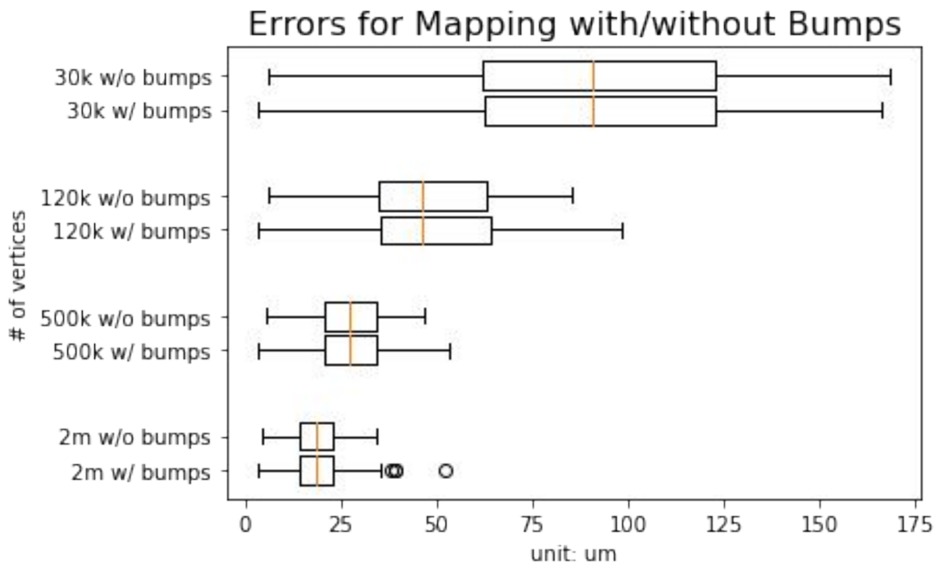
# of sampling points		
30 k	91.2	168
126 k	48.1	85.1
500 k	27.3	47.0
2 Mio	18.5	34.5
infinite	14.3 (= distance errors)	

Experiment with smooth retinal (sphere)

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Deformed retinal surface

Results and comparison



This mapping method is robust against macula (bumps).

Resource: Edwards T L, Xue K, Meenink H C M, et al. First-in-human study of the safety and viability of intraocular robotic surgery[J]. Nature Biomedical Engineering, 2018.

Comparison & Conclusion

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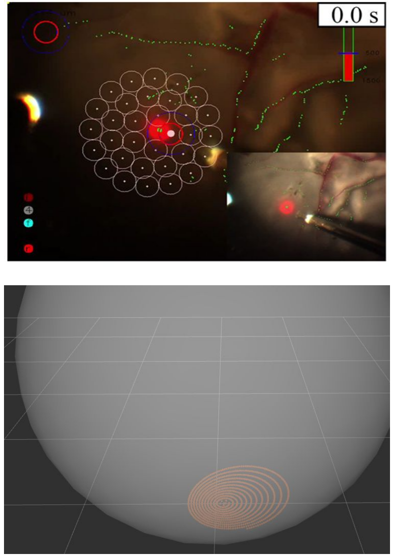
Tests Comparison



Two mapping methods from Yang and us.
Top: eyeSLAM. Bottom: our mapping method.

	eyeSLAM	Our Method
Method	Reconstruction	Reconstruction
Accuracy (um)	150 (open-sky)	14 (in simulation)
Mapping object	Retinal plane	Retinal surface
Mapping result	Plane	Point cloud
Robustness to deformed retinal	Unknown	Robust

Resource: S. Yang, J. N. Martel, L. A. Lobes Jr, and C. N. Riviere, “Techniques for robot-aided intraocular surgery using monocular vision,” The International journal of robotics research, vol. 37, no. 8, pp. 931–952, 2018.

Resources

Sources

[1] Mingchuan Zhou , Felix Hennerkes,Nassir Navab"Theoretical Error Analysis of Spotlight-based Instrument Localization for Retinal Surgery" RAL-ICRA (2021)..

[2] G. Bradski. "The OpenCV Library." In: Dr. Dobb's Journal of Software Tools (2000).

[3] B. O. Community. Blender - a 3D modelling and rendering package. Blender Foundation. Stichting Blender Foundation, Amsterdam, 2018.

[4] W. H. Organization. World report on vision. Tech. rep. World Health Organization, 2019.

[5] A. Routray, R. A. MacLachlan, J. N. Martel, and C. N. Riviere. "Real-Time Incremental Estimation of Retinal Surface Using Laser Aiming Beam." In: 2019 International Symposium on Medical Robotics (ISMR). 2019, pp. 1–5. 59 Bibliography

[6] S. Yang, J. N. Martel, L. A. Lobes Jr, and C. N. Riviere. "Techniques for robotaided intraocular surgery using monocular vision." In: The International journal of robotics research 37.8 (2018), pp. 931–952.

[7]Braun D, Yang S, Martel JN, et al. EyeSLAM: Real-time localization and mapping of retinal vessels during intraocular microsurgery. International Journal of Medical Robotics and Computer Assisted Surgery 14(1): e1848.(2018)

[8]Yang S, MacLachlan RA, Martel JN, et al. Comparative evaluation of handheld robot-aided intraocular laser surgery. IEEE Transactions on Robotics 32(1): 246–251.(2016)

[9]S. Yang, J. N. Martel, L. A. Lobes Jr, and C. N. Riviere, "Techniques for robot-aided intraocular surgery using monocular vision," The International journal of robotics research, vol. 37, no. 8, pp. 931–952, 2018.