

Tele-operation Control of a High Dexterity Robot for Vitreoretinal Surgery

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Clinical motivation

Vitreoretinal surgery is a highly delicate and difficult intraocular surgery that requires the operation on the retina deep within the eye. Examples of this surgery are epiretinal membrane peeling and retinal vein cannulation. Such surgeries are very demanding, requiring exceptional precision to operate on micron scale targets presented by the retina while also maneuvering in a tightly constrained and fragile workspace [1].

Therefore, it poses many challenges for the physicians. The primary issue arises from physiological hand tremor, which will cause trouble during surgery. For example, any slight jerking of the hand formed during retinal peeling can result in retinal tears, causing irreversible blindness to the underlying retina with almost no regenerative capacity.[2] Similarly, exerting forces > 7.5 mN to the retina could result in retinal tears, forces which are too fine to be felt by a human. All these factors result in an exceptional level of training that surgeons must undergo to be able to perform these surgeries [3][4].

Background

To resolve the above stated issues, researcher at Johns Hopkins University, AMIRO LCSR, developed a surgical robotic system, a Steady Hand Eye Robot (SHER), which performs robot-controlled surgery, allowing surgeons to mitigate (filter) physiological tremor affects and provide them with haptic force feedback. Systems like SHER can potentially address a lot of the issues that eye surgeons face in the OR. This impedance style robot (Fig. 1, B), drastically reduced the effects of tremor in surgery.

However, even with SHER, there are still some operative procedures that may not be easily executable, given the limited flexibility of the end effector. A straight needle attached to the end-effector of SHER does not provide enough dexterity for surgeons operating inside the eye, with surgeons often having to move the eye to navigate. Therefore, a 2 DoF Integrated Robotic Intraocular Snake (IRIS) (Fig. 1, C) was designed and attached to the SHER end-effector. This eliminated the need to move the eye by employing a more flexible end-effector.

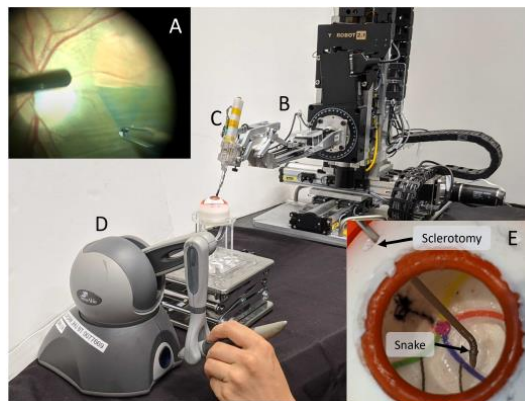


Figure 1. Envisioned high dexterity intraocular manipulator: (A) Epiretinal membrane peeling; (B) Steady Hand Eye Robot; (C) Integrated robotic intraocular snake robot; (D) Phantom Omni; (E) Distal snake-like tool-end inside eye phantom [5].

Existing approaches include teleoperation of both the snake and the eye robot, but separately, as well as a cooperative approach, which involves moving the eye robot by hand, and teleoperating the snake after moving it to the desired position. In recent work done by Kaiyu Shi [5], the 7 DoF integrated system allows the clinician to directly control the position and orientation of the tool tip via a 5-DoF Phantom Omni device (Fig. 1, D).

Specific aim/Goals

The motivation to implement this teleoperation setup is multifold. First and foremost, teleoperating a device like the eye robot help the user/surgeon perform stable and meticulous manipulation, which can understandably improve surgical performance. In addition, replacing the traditional stiff end effector with a snake robot can bring benefits, such as expanding the working space, enhancing flexibility, and reducing the risk of causing injury to the eye to some extent.

Therefore, the main goal of the project is to implement the simulation of the combined teleoperation system in Asynchronous multi-body framework (AMBF)¹. Simulation is one of the common means of testing robots, it enables researchers to quickly develop, validate and test control algorithms without worrying about damaging the robot. To achieve the goal, the model of the snake robot should be built in Blender according to the CAD drawing and then connected to eye robot in the simulation. Meanwhile, I will develop an AMBF plugin to manipulate the snake robot attached to SHER and interact with an OCT Scan of the eye.

Once the simulation of the teleoperation system is done successfully, we aim to develop and implement a control algorithm on the AMBF model using haptic device. Moreover, we expect to apply the controller on the real robot. Finally, we can design and execute an experimental scenario to validate our control algorithm and establish a framework for moving this system closer to clinical assimilation.

Technical approach

This project aims to implement the simulation of the combined teleoperation system in AMBF, which employs the model of the snake robot in Blender addon and usage of different plugins. In addition to studying plugins for our implementation, we also aim to develop a controller using haptic device in AMBF and further test on the real robot.

AMBF simulation:

AMBF offers a real-time dynamic simulation of robots, free bodies, and multi-link puzzles coupled with real-time haptic interaction via several haptic devices [6]. Compared with Gazebo, AMBF has the advantage of being able to interact with and remove parts of a volumetric model which is of vital importance in medical manipulation like drilling. In the simulation work, the following portions will be included:

1. Blender addon

The blender plugin is to ease the creation of multi-body config files that are used in AMBF. With the aid of the addon, we can model the snake robot from a given CAD drawing and configure the joints that will be used in the simulation.

2. Volumetric Drilling Plugin

The plugin is a basic one for volumetric drilling for skull base surgery with a handheld drill as shown in Fig. 2, with which we can actively modify anatomy with a virtual drill in the simulation. Although the application is not the same as this project, learning how to use this plugin can better help understand the functionality as well as the usage of the plugin.

¹ More detailed information about AMBF is on the website <https://github.com/WPI-AIM/ambf/wiki>

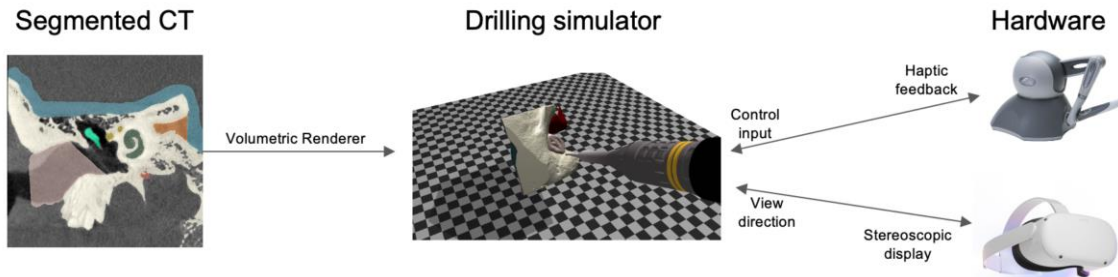


Figure 2. Overview of the virtual drilling simulator for skull-base surgery developed using AMBF [7].

3. Plugin related to UR5 and eye robot

There is other plugin built based on the volumetric drilling plugin to cater to a different application, i.e. a robot with a snake attached to it for spine/ortho surgery. Inspired by this plugin, we can build the combined system of eye robot and snake robot for vitreoretinal surgery. In this case, the functionality and performance of the snake robot can be tested in AMBF. Also, the simulation will be used to develop and test control strategies and allow for visualization of feasibility more-rapidly.

Control Algorithm:

In order to design control algorithms for snake robots, we need to have knowledge about robot kinematics. Given that modeling the kinematics of a continuum robot is not as straightforward as a traditional manipulator, our goal is to develop an experimental forward kinematics and calibrate the motion of a new snake robot (I²RIS) to produce a mapping between the execution space of the snake robot and its configuration space, and finally to its task space. This will allow for accurate forward kinematic mapping, which is essential for modeling any form of inverse kinematics.

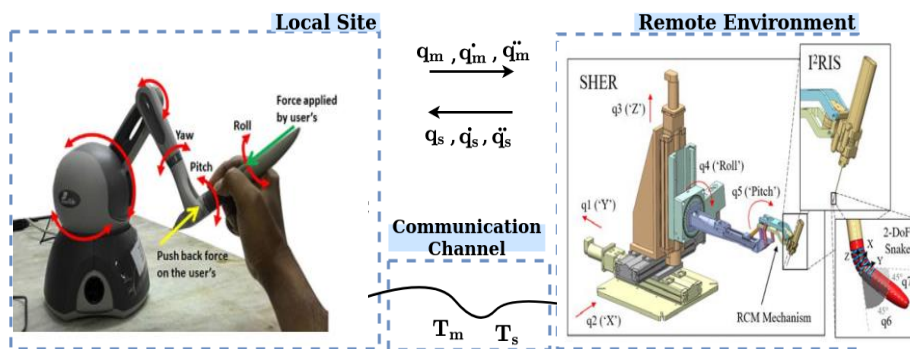


Figure 3. Teleoperation control framework, 5 DoF Phantom Omni as a local robot on the left side, and the hybrid 7 DoF Snake & Eye Robot (I²RIS + SHER 2.1) as remote robot on the right.

To perform autonomous position control or teleoperation with virtual fixtures using snake robot, it is necessary to have a good model for input-output mapping that will enhance operation accuracy and performance. Several experimental and analytical methods for kinematics modeling in snake robots have been developed, a probabilistic data-driven kinematic model with a hysteresis compensation algorithm will be used for this project, which is more suitable for nonlinear mapping between the input signals and the outputs (snake bending angles, yaw and pitch) [8].

Deliverables

Minimum

- Developing a simulation model for the Eye Robot and the Eye Snake systems in AMBF
 - Learn AMBF + ADF + Blender addon
 - Learn about how to use various plugin
 - Get familiar with volume and 3D scans

Expected

- Develop and implement a control algorithm on the AMBF model using a haptic device

Maximum

- Implement the controller on the real robots

Dependencies

Dependency	Status	Point of Contact	Fallback/Contingency measure	Need by date	Result in case of failure
Eye Robot accessibility	Readily available	Mojtaba Esfandiari / Dr. Iordachita	No contingency	N/A	N/A
Snake Robot accessibility	Readily available	Mojtaba Esfandiari / Dr. Iordachita	No contingency	N/A	N/A
Phantom Omni	Available	Mojtaba Esfandiari / Dr. Iordachita	No contingency	N/A	N/A
Eye robot and snake robot CAD models	Not yet obtained	Mojtaba Esfandiari / Dr. Iordachita	No contingency	03/13/2023	Delay in the implementation of the simulation
Access to robotorium	Obtained	Mojtaba Esfandiari	No contingency	03/06/2023	N/A
Access to snake robot plugin	Obtained	Adnan Munawar	No contingency	ongoing	N/A
CT data / the loop X machine	Not yet obtained	Mojtaba Esfandiari / Dr. Iordachita	If no CT data, use the loop X machine to collect the eyeball 3D scan	03/20/2023	

Some of the dependencies for this project haven't been met, Mojtaba will be responsible to send me the data/model when necessary.

Timeline

Tasks	2/20	2/27	3/6	3/13	3/20	3/27	4/3	4/10	4/17	4/23
Learn AMBF + ADF + Blender addon	[Red shaded]									
Learn about how to use the plugin (volumetric_drilling)		[Yellow shaded]	[Orange shaded]							
Get familiar with volume and 3D scans										
Learn other plugins related to snake robot and UR5			[Orange shaded]							
Implement and incorporate eye robot and snake robot in AMBF				[Green shaded]	[Green shaded]	[Green shaded]				
Develop a controller for the combined teleoperation of the eye robot and snake robot (using haptic device)					[Blue shaded]	[Blue shaded]	[Blue shaded]	[Blue shaded]	[Blue shaded]	[Blue shaded]
Implement the controller on the real robots								[Purple shaded]	[Purple shaded]	[Purple shaded]
Develop comprehensive report										[Dark Blue shaded]

The shaded regions of the timeline represent the buffer period. This is the period a given task can be delayed in completion beyond its expected conclusion date. The timeline is primarily driven by the expected deliverables.

Milestones

Milestone	Start Date	End date	Buffer date
Learn AMBF + Blender	02/20	02/27	N/A
Learn about different AMBF plugins	02/27	03/13	N/A
Incorporate eye robot and snake robot in AMBF	03/13	03/27	04/3
Develop a controller using haptic device	04/3	04/17	04/27
Implement controller on real robot	04/11	04/23	04/28

Management plan

The management plan involves weekly meetings with Mojtaba Esfandiari and Adnan Munawar on Tuesday afternoon 3-4 pm. We further have a bi-weekly meeting with Dr. Iulian Iordachita on Friday afternoon (Time may change due to schedule).

I will maintain communication with mentors through Microsoft Teams, and other relevant messaging services. A shared OneDrive folder is employed to maintain relevant project materials, including but not limited to presentations, reference literature, and reference code.

Reading list

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Song, J., Gonenc, B., Guo, J., & Iordachita, I. (2017, May). Intraocular snake integrated with the steady-hand eye robot for assisted retinal microsurgery. In *2017 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 6724-6729). IEEE.

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