

CIS II critical review: Optimization-based Concurrent Control of a High Dexterity Robot for Vitreoretinal Surgery

Team 22 (Tele-operation Control of a High Dexterity Robot for Vitreoretinal Surgery)

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Project summary

Vitreoretinal surgery is a highly delicate and difficult surgery kind of intraocular surgery, one that is concerned with operating deep within the eye on the retina. Examples of this surgery are epiretinal membrane peeling and retinal vein cannulation. However, there are several factors that could be a potential risk during such surgeries. The primary issue arises from physiological hand tremor, which, as faint as it may be, can still result complications during surgery. As such, our project aims to implement teleoperative control of a high dexterity robot that is employed for tremor reduction of the surgeon's hand.

We intend to develop and implement a teleoperation algorithm for controlling 7 D.O.F hybrid robot with 5 D.O.F Phantom Omni. The 7 D.O.F hybrid robot consists of a base robot, which has 5 D.O.F, and a snake robot, which has 2 D.O.F. Our teleoperation algorithm will revolve around the implementation of an optimization function, given the discrepancy between the degrees of freedom, as well as well-established constraints for within the eye workspace.

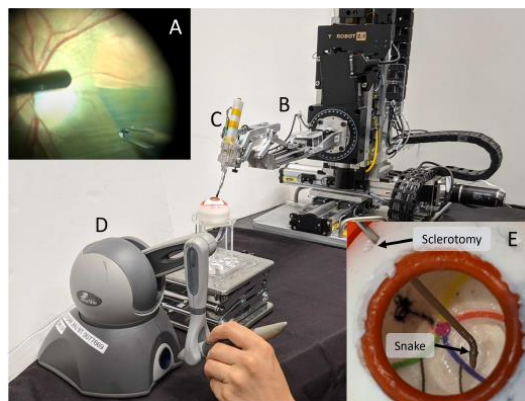


Fig 1. Envisioned high dexterity intraocular manipulator: (A) Epiretinal membrane peeling; (B) Steady Hand Eye Robot; (C) Integrated robotic intraocular snake robot; (D) Phantom Omni; (E) Distal snake-like tool-end inside eye phantom [3].

Selected paper background and goals

The paper we have chosen for our critical review is “Optimization-based Concurrent Control of a High Dexterity Robot for Vitreoretinal Surgery.” The clinical motivation for this paper

stems from the high-risk nature of vitreoretinal surgery, and the subsequent skill and training that is required to effectively perform this surgery. Lack of fine force feedback in humans, or even faint physiological tremors, can result in damage to the eye during surgery.

As such, the paper seeks to improve upon the current paradigm of robotic assisted vitreoretinal surgery, by simulating the implementation of teleoperative control of a hybrid high-dexterity robot, which was previously controlled with its two parts being operated separately (the SHER and I2RIS (snake) robots). By implementing this teleoperation of the 7 D.O.F hybrid robot with a 5 D.O.F Phantom Omni, the authors aim to not only prove the greater dexterity afforded by this new system, but also hope to reduce the cognitive load of using such a system in actuality.

Relevance

This paper addresses key elements of our project, by implementing teleoperative control of the same 7 D.O.F hybrid system with a 5 D.O.F Phantom Omni, albeit in simulation. Though we aim to implement teleoperative control on the real hybrid setup, and while there is a distinct enough difference between real and simulated teleoperative control, this paper establishes a key framework for the construction of the teleoperative system, including but not limited to the kinematic relationships, and the teleoperation algorithm used to map the movement of the 5 D.O.F phantom Omni to the 7 D.O.F hybrid robot.

Moreover, the kinematic chain of the robot utilized in the paper is the same for the robot we aim to use in our project, which makes the potential comparison of results between our work and this paper's test viable, not to mention the ease of modifying the proposed teleoperation algorithm without danger of incorrect modeling of the system. This paper also serves as a proof of concept, as the results of the teleoperation control are satisfactory enough to justify the implementation on the real robot.

Methods

The authors implemented their teleoperation algorithm, including the forward kinematics and the inverse kinematics optimizer, in MATLAB, and interfaced to Gazebo (via ROS) to setup the simulation of the hybrid system. The authors further used URDF (Unified Robot Description Format) files (which we assume were prepared in-house). Measurements of the system were obtained from CAD files.

As mentioned, the hardware used for this testing (or the hardware that was simulated) were the SHER and I2RIS robots, both of which have undergone several design iterations, as well as the Phantom Omni. The Phantom Omni's end effector's end position's workspace was scaled to the size of the vitreous space.

The forward kinematics of the system were calculated by multiplying the forward kinematic functions of the SHER and the I2RIS robot. SHER's forward kinematic chain was modeled as three linear transformations and two rotational transformations. I2RIS's forward kinematic mapping is developed by modeling each two pair of consecutive intermediate disks of the snake robot as part of two cylinders that are rolling relative to each other's surface about a virtual point. The rotation axis

between every other pair of segments/disks alternates orthogonally. Slippage and friction between the rolling cylinders are not considered though.

As part of the teleoperative algorithm (and possibly the assumptions), the authors define their new frame of reference, at the position of the sclerotomy. Thus, they are able to reduce the degrees of freedom from 7 to 5, especially since the sclerotomy point lies on the line of the mechanical RCM. This is done by disregarding the x and y movements that are present in the “robot” reference frame (the 7 D.O.F frame), as such movements are not accessible for the tool is in the eye. Moreover, it is computationally less expensive to calculate the Jacobian for five variables, as opposed to seven (especially in real-time applications).

The authors then describe their constraints, three for the trajectory, the most important of which restricting movement within the eye so as to avoid a collision, and three for the optimization of the objective function, the most important of which being the implicit understand that the inverse kinematics is solved in the eye frame with the reduce DOF. The authors then propose the following objective function, and implement the pseudo code as depicted in fig 2 A.

$$Objective = ||Jacobian * \Delta q - \Delta X||$$

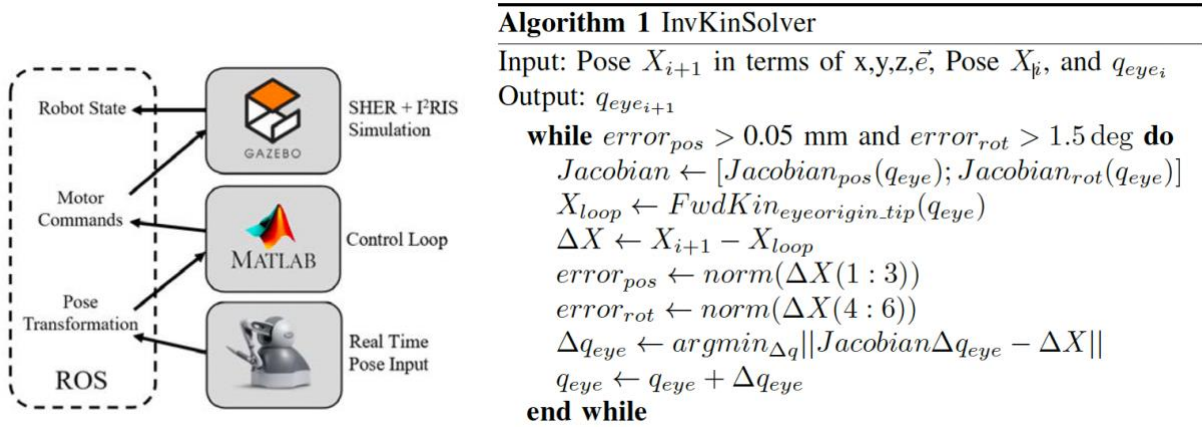


Fig 2. A) software architecture B) Pseudocode of teleoperation algorithm

Some key assumptions were made for the system to work, such as perfect registration of the target eye, prior knowledge of the sclerotomy incision point, and a perfect, rigid nature of the target eye, amongst others.

Results and conclusions

The authors conducted **four** kinds of absolute and comparative studies:

1. Preplanned path traversal
2. Phantom Omni real time control
3. Comparison between dexterous tool and rigid tool
4. Real time execution

Preplanned path traversal

The authors analyzed the movement of the hybrid system along two preplanned paths, both emulating the appropriate movements during surgery. By recording the position of the tool tip, the authors reported that the error between the inputs (the path trajectory) and the actual tool tip were within the tolerance band used for the inverse kinematics solver.

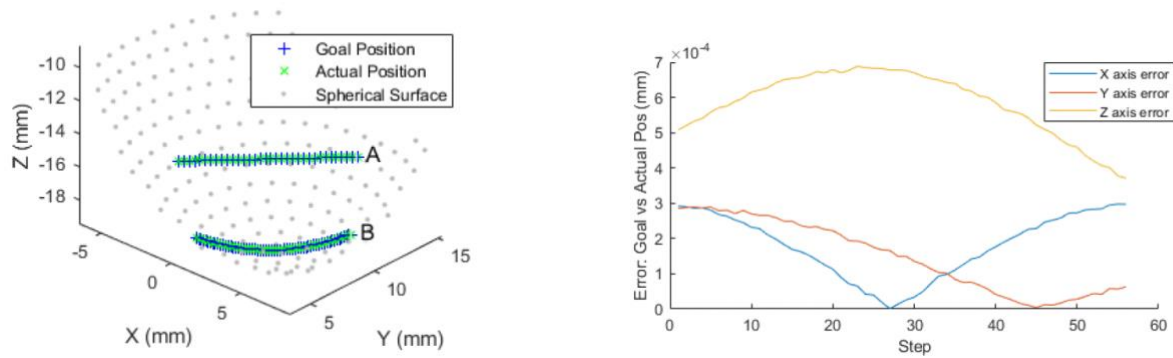


Fig 3. A) Planned path traversal : (A) linear path; (B) Arc on surface B) Error between target and actual position for arc path B

Phantom Omni real time control

This test was to ensure effective implementation of the teleoperation algorithm to control the hybrid system with the phantom omni. As fig. 4 shows, the Omni's movements were tracked by the system until the system encountered the constraints, at which point you can observe the deviation of the phantom Omni's tool tip position from the actual position. The authors conducted the same test for more complex movement, which showed similar results. It should be noted that there were slightly more mismatched movements (but still keeping with the expected trend of following-until-constrained), which can presumably be contributed to the more complex nature of the movement, which would naturally strain the system.

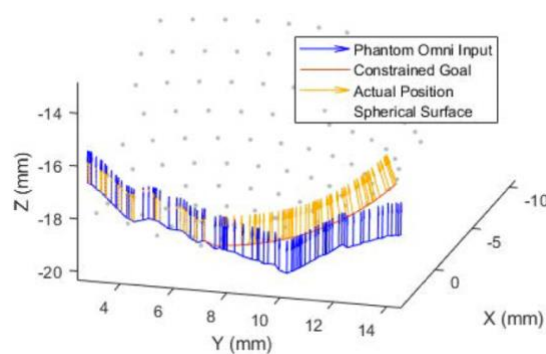


Fig 4. Real time input constrained into the intraocular space

Comparison between dexterous tool and rigid tool

As was cited in the background section of the paper, the dexterous snake tool would grant surgeons/users greater dexterity intra-operatively, allowing them to reach positions that cannot be reached with a rigid tool, through paths that cannot be traversed with a rigid tool. The results were very positive, as can be seen in fig 5. The dexterous tool afforded the users 180% more workable space relative to the rigid tool. Moreover, areas that both tools could reach, could be reached through increased number of trajectories by the flexible tool, compared to the rigid tool.

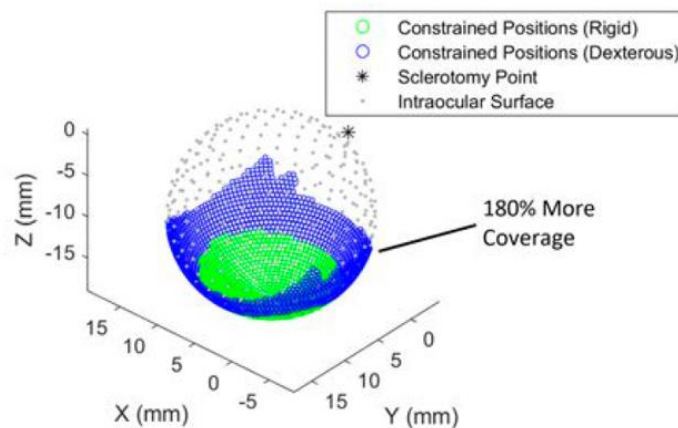


Fig 5: Comparison of rigid vs dexterous I2RLS reachability

Effectiveness of system in real-time

The potential introduction of this system in the OR would be futile if the system was not able to receive commands and execute movements in real time. Thus, this evaluation sought to deduce the responsiveness of the system.

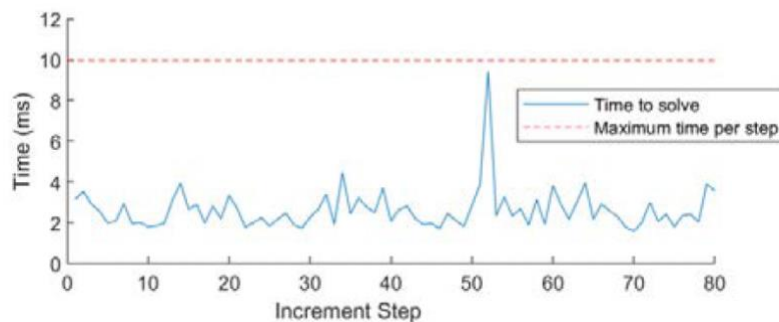


Fig 6. Time to solve inverse kinematics

As the system can solve its inverse kinematics optimization sooner than the next step is taken, this proves that the system is capable of operating in real time. It should be noted that the paper highlights the inverse relationship between time cost of solving the inverse kinematics and maximum speed was non-linear

On a conclusive note, the paper reiterated its validating results, proving that the teleoperation of the highly dexterous system was able to accurately operate within the assigned constraints, and displayed greater flexibility than a rigid system, all while proving that it was wholly applicable on a real robot.

Critical assessment

Strengths

This paper offers a great framework for our project, given the details of the assumptions, and the teleoperation algorithm. To begin with, their choice to implement a simulation of the teleoperation system was sound, as this allowed them to work offline, and test their implementation without potentially putting the real system at risk.

Moreover, their numerical inverse kinematic approach generates optimized robot states while considering the robot joints constraints such as joint position/velocity limits as well as robot-eye interaction constraints such as RCM point, needle insertion depth, etc. Considering that this is a simulation, the implementation of such constraints is appreciated.

In addition, the variety of validating tests was impressive, with the authors providing four different forms of evaluation. In addition to the variety, the success in virtually all categories proved that this system can be implemented on a real robot, with great potential for success. One key metric discussed in this paper was the ability of the teleoperative algorithm to operate in real time, which is critical in evaluating the viability of implementing the system in actuality.

Furthermore, the use of an alternative frame of reference (eye frame), makes the problem less computationally expensive, as the Jacobian only has to be calculated for five variables, instead of seven, which further impact the real-time operation of the robot.

Critique

The paper assumes that the hybrid system is already at the trocar point/RCM, which is an oversimplification of the problem (part III.C). By making this oversimplification, the authors navigate around the need to derive a constraint for maintaining the RCM/trocar point, which in reality is a critical step, given the great need for the hybrid system to not make movements that violate the RCM point and damage the eye in the process.

Building off this, the number, and quality, of constraints applied to the simulated teleoperative control could have been addressed better. There are no limits on the joint angles, or constraints to restrict any collisions of the eye-robot end-effector (which holds the snake robot) from colliding with the inside surface of the eye. The paper further fails to provide any mathematical

models or equations for the constraints mentioned in Part IV.A, or in the subsequent snippet of pseudo code.

The kinematic mapping model of the snake proposed by the paper is further subject to scrutiny. The paper maps the bending of the snake as a function of the movement of each individual disk (which make up the snake) relative to the previous cylindrical surface. In short, they defined a kinematic chain between intermediate disks to represent the snake tip position and orientation. However, on the real robot, the intermediate disks angles can neither be measured nor controlled separately. Therefore, an experimental forward kinematic needs to be developed to do the mapping between the actuation space (snake motor encoder angles) to the task space (snake tip spatial position and orientation).

Another criticism of the paper stems from their limited data sets. It can be inferred that only two paths were tested for the preplanned path traversal test, and a single iteration of tests for two movements for the Phantom Omni real time control test. While these results are promising, they lack the strength of repeat testing, and inevitably invite slight skepticism. Moreover, the paper could have done with more quantitative analysis of the results, as opposed to simple graphic projections of the results. A more concretely quantified display of success may add credibility to the seemingly successful implementation of the teleoperation algorithm.

Conclusion

Despite the numerous critiques of the paper's approach, primarily in the realm of the implementation of its teleoperation algorithm, we strongly believe that the framework established by the paper is applicable to our research, and indeed also serves as the basis for a considerable amount of the progress made thus far. We have extrapolated from the suggested objective function and constraints, modifying them to fit our real-world conditions, and hope to produce test results that show similar success as those highlighted in the paper.

References

Shi, Kaiyu; Zhou, Yishun; Ebrahimi, Ali; Li, Gang; Iordachita, Iulian (2022), Optimization-based Concurrent Control of a High Dexterity Robot for Vitreoretinal Surgery. Manuscript submitted for publication