Paper Report

Development and Experimental Evaluation of Concurrent Control of a Robotic Arm and Continuum Manipulator for Osteolytic Lesion Treatment

Paul Wilkening, Farshid Alambeigi, Ryan J. Murphy, Russell H. Taylor, Mehran Armand

Kaiyu Shi | kshi10@jhu.edu

Table of Contents

CIS II Project Overview

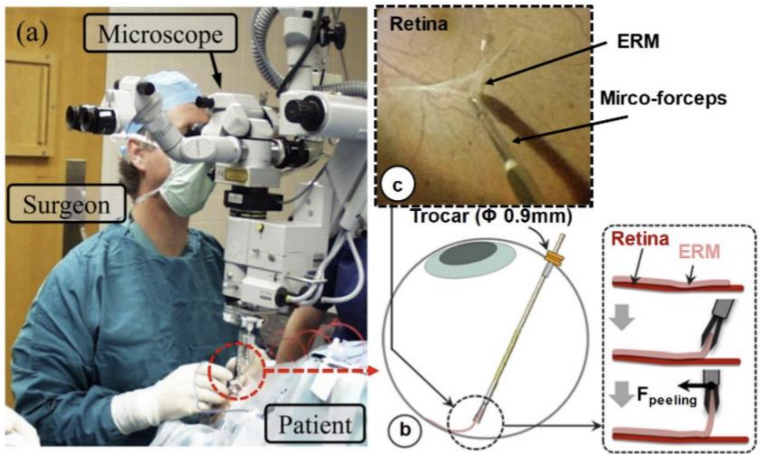


Figure 1: Epiretinal Membrane Peeling

Vitreoretinal surgery is a type of micro-surgery that requires high dexterity and sensitivity from the surgeon. Some procedures, such as Epiretinal membrane peeling (Fig. 1), require force sensitivity as high as 7.5 mN to avoid irreversible damage to the patient [4]. As such, it can be beneficial to use force sensors in conjunction with robot assisted surgery (RAS) for such procedures.

The Intra-ocular High Dexterity Manipulation project aims to achieve this by combining a distal end "I^{2}RIS" robot with the "Steady Hand Eye Robot" (SHER) for a concurrently controlled robot that can achieve configurations that respect the constraints of the space while maintaining low error from the target position/orientation [2].

Paper Selection

The paper that was selected is titled "Development and Experimental Evaluation of Concurrent Control of a Robotic Arm and Continuum Manipulator for Osteolytic Lesion Treatment [1]. It was published in 2017.

Summary

The paper details the development and evaluation of an experimental manipulator designed for treating osteolytic lesions. It describes the setup of the system and presents the kinematics of the combined robots. A method of calibration for the distal end's approximated forward kinematics is presented, involving the Polaris NDI system. Virtual fixture constraints are used to optimize the trajectory of the system in a safe manner to the patient. The experimental system is tested by having it follow a goal trajectory and examining the error between end tip position and goal.

Relevance

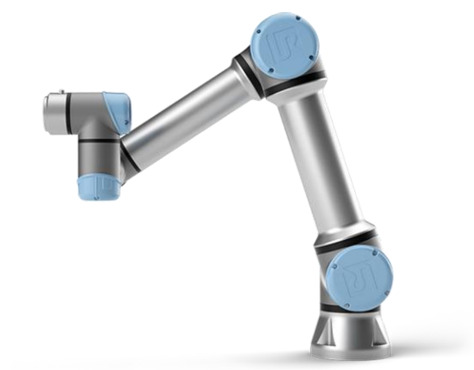
This paper is relevant to Group 7's project because it describes a similar robotic system to address a similar type of problem, where the operating space can benefit from dexterous manipulation controlled by a computer. The implementation of concurrent control with constraints in this paper has much overlap with the intended implementation for Group 7. Furthermore, this paper discusses the issues with error on the distal end due to wire friction and collision with surfaces. This may be important to consider and discuss.

Introduction

Motivation

Osteolysis can occur from the wearing of polyethylene liner against the bone in hip replacements. The Acetabular cup, which holds the artificial hip joint, obstructs open access to the affected area by the surgeon. To make the surgery less invasive, it is desirable to treat the lesion by first drilling the affected area through the screw hole in the cup, and then scraping off the remaining lesion material before sucking everything out. To operate in an area wider than the width of the hole, it is necessary to have a manipulator capable of bending.

Robot Description



UR5 (Universal Robotics) [5]

The robot consists of two principal components. A UR5 is used to position the distal manipulator, and provides 6 degrees of freedom, enabling local change of motion in any direction/orientation. Attached to the end of the UR5 robot is a base, which provides a rigid transformation to the CDM.

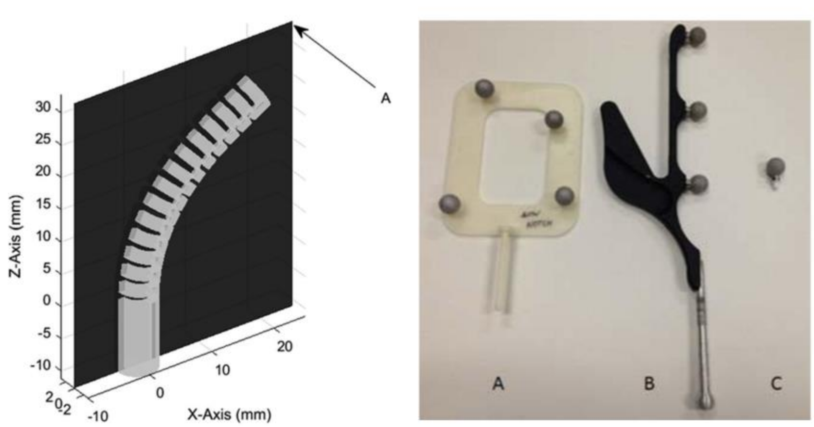


Figure 2: CDM and Calibration Objects [1]

The CDM (Continuum Dexterous Manipulator) is a one degree of freedom distal manipulator actuated by pulling/pushing a wire (Fig. 2, left). The relationship between length of wire and position is calibrated by using Polaris NDI tracking. The CDM is placed within a tracked calibration rig (Fig. 2, A) and the tip of the CDM is fitted a tracking marker (Fig. 2, C).

$$p_{\mathrm{CDM},x} = B_n\left(l\right)$$

$$p_{\mathrm{CDM},z} = \sum_{i=1}^{3} a_i \sin\left(b_i p_{\mathrm{CDM},x} + c_i\right).$$

[1]

A Bernstein polynomial is fitted to represent x and z transformations for a given wire length l.

Kinematics

$$F_{\mathrm{Combined}}\left(q\right) = F_{\mathrm{UR5}}\left(q_{\mathrm{UR5}}\right) * F_{\mathrm{Base}} * p_{\mathrm{CDM}}$$

[1]

The combined positional transformation is represented by the F_{UR5} transformation multiplied by the fixed transformation F_{base}, and then multiplied by the positional transformation p_{CDM}. The input q is a vector of 7 values, representing the 7 combined degrees of freedom.

Jacobian

$$J_{\mathrm{Combined}}\left(q\right) = \left[\, J_{\mathrm{UR5}}\left(q\right) J_{\mathrm{CDM}}\left(q\right)\right];\; J_{\mathrm{Combined}}\left(q\right) \in \mathbb{R}^{6\times7}$$

[1]

The combined Jacobian, which is used to solve constrained optimization problems, is composed of the Jacobians of the UR5 and the CDM.

Constrained Optimization

$$\mathrm{argmin}_{dq}\left|\left|J_{\mathrm{Combined}} * dq - dx_{obj}\right|\right|^2.$$

[1]

To move the manipulator, an objective is minimized and solved for the dq that needs to be applied to the current q. The optimization is subject to 4 constraints that guarantee the motion is “safe”.

$$dq \geq dq_{\mathrm{Lower}}; -dq \geq -dq_{\mathrm{Upper}}$$

[1]

This constraint limits the amount of change each joint can be subject to each time step, which is lower or equal to the maximum velocity of each joint.

$$H * J_{\mathrm{Closest}} * dq_{\mathrm{UR5}} \geq h$$

[1]

This constraint limits the distance the nearest point to the rotational center of motion (RCM) can be from the RCM. The Jacobian is calculated for the point that is closest to the RCM at the given moment.

$$axis^T{}_{\text{des}} * J_{\text{Base}} * dq \geq \cos(\theta_{\text{tol}}) - axis_{\text{des}} * axis_{\text{cur}}$$ [1]

This constraint constrains the axis of the base to be within a “cone”, so that there is no collision with the ring of the screw hole.

$$n^T * J_{\text{Base}} * dq \geq e - n^T * p_{\text{Base}}$$ [1]

This constraint represents a virtual wall that the end of the base of the CDM cannot pass a certain distance, so that the CDM cannot collide and deform.

Evaluation

The system was evaluated by moving the CDM tip along a predefined goal trajectory. The tip of the CDM was optically tracked by Polaris NDI. The results were compared with the path to produce an estimated error bound (Fig. 3).

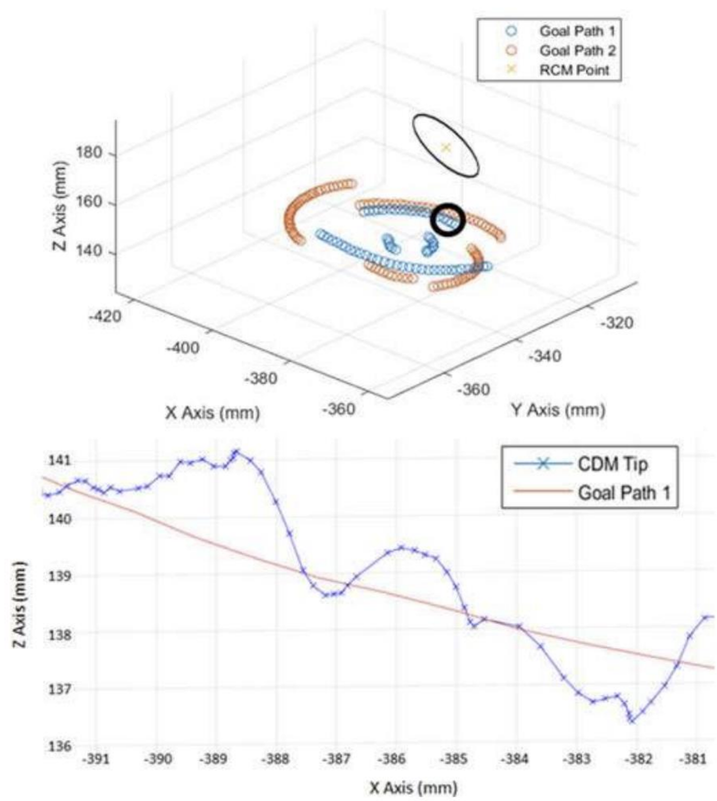


Figure 3: Experimental Evaluation [1]

TABLE I
SUMMARY OF CDM TIP ERRORS FROM FOLLOWING TWO PATHS FOR MULTIPLE TRIALS

	Path 1		
	Trial 1	Trial 2	Trial 3
Mean Error (mm)	0.46	0.43	0.51
Maximum Error (mm)	1.0	1.0	1.0
Stdev of Error (mm)	0.31	0.28	0.3
	Path 2		
	Trial 1	Trial 2	
Mean Error (mm)	0.34	0.35	
Maximum Error (mm)	1.0	1.0	
Stdev of Error (mm)	0.3	0.29	

Figure 4: Table of Results [1]

Conclusion

The manipulator was able to reach proscribed positions that would be behind the acetabular cup. The system was able to calculate new joint positions in approximately 20ms (50 Hz), which is sufficient for real time operation. The mean error between the CDM and proscribed path is 0.42 mm (RMS value). The maximum error was 1.0 mm (Fig. 4). Major sources of error include the Polaris tracker (0.35 mm RMS), the CDM due to deformation and unpredictable friction, and the UR5. Additionally, the CDM component used for calibration was not the same one that was used for the evaluation.

Future Work

For future work it was discussed that the polar tracker on the CDM tip could be used to provide active feedback, which would help with the approximation of the shape of the CDM and therefore the Jacobian. Benefits of implementing this would include lower error, faster convergence than the existing “open loop” calibrated Jacobian. Additionally, it was discussed to further evaluate the system with less limits on the allowed workspace.

Assessment

Pros

This paper was clear and concise with mathematical formulations and presentation. The visualization and explanation of how the constraints are implemented were also very helpful. Discussing the sources of error, especially for the CDM, is beneficial as well.

Cons

This paper was not clear on the methodology from which the 1.0 mm maximum error bound was produced. The experiments for evaluation were not comprehensively presented and could stand for more elaboration. The use of a different CDM for calibration did not make much sense in terms of minimizing sources of error. Lastly, there could have been more explanation on how the optical tracking would be used to improve the Jacobian in a surgical setting.

References

[1] P. Wilkening, F. Alambeigi, R. J. Murphy, R. H. Taylor and M. Armand, "Development and Experimental Evaluation of Concurrent Control of a Robotic Arm and Continuum Manipulator for Osteolytic Lesion Treatment," in IEEE Robotics and Automation Letters, vol. 2, no. 3, pp. 1625-1631, July 2017, doi: 10.1109/LRA.2017.2678543.

[2] Makoto Jinno, Gang Li, Niravkumar Patel, Iulian Iordachita, "An Integrated High -dexterity Cooperative Robotic Assistant for Intraocular Micromanipulation", 2021., Kokushikan University

[3] 3D Systems. "Touch." *3D Systems*, 4 June 2020, www.3dsystems.com/haptics-devices/touch.

[4] P. Gupta, P. Jensen, and E. de Juan, "Surgical forces and tactile perception during retinal microsurgery," in International Conference on Medical Image Computing and Computer Assisted Intervention, vol. 1679, 1999, pp. 1218–1225

[5] https://www.universal-robots.com/products/ur5-robot/