

IMPROVING THE TRANSPARENCY OF THE GALEN ROBOT

CIS-2 Background Literature Review by Vishnu Kolal

I. PROJECT SUMMARY

The Galen Robot (Mk-2) is a prototype Delta robot manipulator intended for surgical use. It comes equipped with a 6-axis F/T sensor mounted between the robot and the end effector. The sensor provides vital information which is used to control the robot in a hand-over-hand control mode where a surgeon and the robot, both, hold the tool together. The surgeon controls the tool path directly while the robot provides a steady platform by eliminating hand tremors and enforcing hard or soft limits. The tool is typically a surgical drill intended for cutting bone. The robot has great potential to improve the safety and efficacy of certain surgical procedures including Laryngeal surgery, Stapes Surgery, Mastoidectomy, etc. However, the robot is a prototype and needs significant improvement before it is ready for use in an OR.

The goal of this project, as stated, is to improve the transparency of the Galen hand-over-hand surgical robot i.e. to make the tool feel 'weightless' in the hands of the operator. Currently, the feel of the tool while used in the hand-over-hand control mode is sub-par and sluggish. This project aims to improve this 'feel' and make the robot more responsive to operator force input.



Figure 1: Galen Robot Mk2. Image curtesy www.galenrobotics.com

II. PAPER SELECTION

In order to improve the transparency of the robot and devise methods to evaluate the same, a deep understanding of the construction and functioning of the robot is necessary. For this reason, the paper describing the robot in the most in-depth detail was chosen. In this case, the PhD dissertation submitted by the late Kevin C. Olds. This detailed document describes the philosophy behind, and the development of two surgical robot systems, namely, the Robo-ELF (Robotics Endo-Laryngeal Flexible) and the REMS (Robotic Ear Nose and Throat Microsurgery System).

For the purpose of this critical review, we will focus on chapter 3 section 15 of the PhD dissertation. This chapter outlines the design requirements, performance indices, kinematics, mechanical design and optimization, electronics, software, and validation of the REMS. Chapter 15 describes the software behind the robot and discusses the admittance control algorithm in detail. The contents of this chapter are highly relevant to the goals of this project.

III. PROBLEM SUMMARY

The recent shift in paradigm towards minimally invasive surgical procedures bring new challenges such as limited visibility, reduced working area near sensitive tissues, decreased precision, poor sensory feedback. Even though surgical robotic systems have been developed to address these challenges, there exists no dedicated robotic systems for Otolaryngology-Head and Neck surgery.

The dissertation presents the design, development and validation of the two mentioned robotic systems.

IV. SIGNIFICANCE

The REMS robot has potentially limitless applications such as eliminating hand tremors, imposing virtual fixtures that prevent the operator from damaging sensitive organs, drilling out of pockets in bone structures with near perfect precision, automated guided biopsies and maybe even fully automated surgery in the not-so-distant future.

Some of the key Otolaryngology-Head and Neck surgical procedures targeted by the REMS are: Stapedotomy, Cochlear implant surgery, Sinus surgery, Endonasal skull base surgery, microlaryngeal phonosurgery, Laryngeal surgery, mastoidectomy, etc.

V. TECHNICAL OVERVIEW

In this section, we will briefly discuss the software implementation of the admittance controller on the REMS.

The software of the robot primarily resides in two places. The mid, high level controller on a PC and the low level controller, i.e. the Galil controller runs on separate hardware. The REMS utilizes a C++ code running on an Ubuntu PC to perform high level tasks. This high level controller then publishes velocity commands to the low level controller which is responsible for controlling the motor currents.

The admittance controller is formulated in such a way as to allow for solving by a numerical optimizer. The optimizer solves a liner optimization problem of the form

$$\underset{x}{\operatorname{argmin}}(\|Ax - b\|)$$

With the constraints,

$$\begin{aligned} \mathbf{C}\mathbf{x} &\leq \mathbf{d} \\ \mathbf{x}_{min} &\leq \mathbf{x} \leq \mathbf{x}_{max} \end{aligned}$$

This approach aims to determine the incremental joint positions necessary in the next time step based on the commanded input. To do this, a relationship between incremental motion at the end effector and incremental joint position is required. This comes in the form of a Jacobian.

$$\Delta\mathbf{x} = \mathbf{J}\Delta\mathbf{q}$$

Where,

$$\Delta\mathbf{x} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta roll \\ \Delta tilt \end{bmatrix}, \Delta\mathbf{q} = \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \\ \Delta roll \\ \Delta tilt \end{bmatrix}$$

The admittance control is then implemented as:

$$\underset{\Delta\mathbf{q}}{\operatorname{argmin}}(\|\mathbf{G}\mathbf{f} - \mathbf{J}\Delta\mathbf{q}\|)$$

Where, the matrix of admittance gains is \mathbf{G} , and the commanded force vector from the wrist force sensor is \mathbf{f} .

$$\mathbf{G} = \begin{bmatrix} g_{1,1} & 0 & 0 & 0 & 0 \\ 0 & g_{2,2} & 0 & 0 & 0 \\ 0 & 0 & g_{3,3} & 0 & 0 \\ 0 & 0 & 0 & g_{4,4} & 0 \\ 0 & 0 & 0 & 0 & g_{5,5} \end{bmatrix} \quad \mathbf{f} = \begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_{roll} \\ \tau_{tilt} \end{bmatrix}$$

The gains are set in such a way as to maximize the dynamic range by ensuring that the maximum allowable force/torque on the wrist sensor results in the maximum allowable velocity.

Once the incremental motion at each time step is calculated, it can be converted to an incremental velocity by

$$\dot{\mathbf{q}} = \frac{\Delta\mathbf{q}}{\Delta t_{opt}}$$

A major challenge with tuning the gain of the admittance controller is the delicate tradeoff between stability and responsiveness. If the gain is too low, the input from the force sensor is heavily filtered, the hand over hand control of the robot will feel sluggish and heavy but it will be stable. If the gains are too high, the robot will be sensitive to small changes in the force input and the control will feel more responsive and weightless, however, it will also exhibit undesirable instability in the form of oscillations, vibrations and jerky motions. The gains, must therefore be carefully tuned to avoid these effects.

VI. CRITICAL ASSESSMENT

This dissertation is an incredibly important achievement in the field of medical robotics and the fact that a commercial venture of the REMS exists in the form of a startup, Galen Robotics, is a testament to this. The paper does a very good job of describing the clinical motivation behind the two robots and the implementation of control laws to carry out some of these tasks. The paper also sets out independent non-standard indices to assess the performance of the robot and provides detailed testing and validation data.

However, one major critique of the paper that we can offer is the fact that although this paper delves deep into the details of the construction and validation of the robot, it does little to explain the software implementation of the mid and low level controller beyond the basic mathematical formulation. The details of the implementation of the code is a key part of this project and other sources of documentation will need to be reviewed for this purpose.

Another major critique is the fact that although this paper talks about the implementation of the admittance gain and what they should ideally be set to, the paper does not discuss any numerical values for these gains, nor does it discuss any methods on how to determine these gains or assess the transparency of the robot.

VII. CONCLUSION

Overall, this dissertation has provided valuable insight into the workings of the REMS and by extension, the Galen robot. The knowledge gained by analyzing the motivations and development of the robot will go a long way in supporting our efforts to improve the transparency of the robot, although, new methods to assess the transparency will need to be formulated and tested for this project to succeed.

VIII. REFERENCES

- [1] K. Olds, *Robotic Assistant Systems for Otolaryngology-Head and Neck Surgery*, PhD thesis in Biomedical Engineering, Johns Hopkins University, Baltimore, March 2015.