Improving The Transparency Of The Galen Robot

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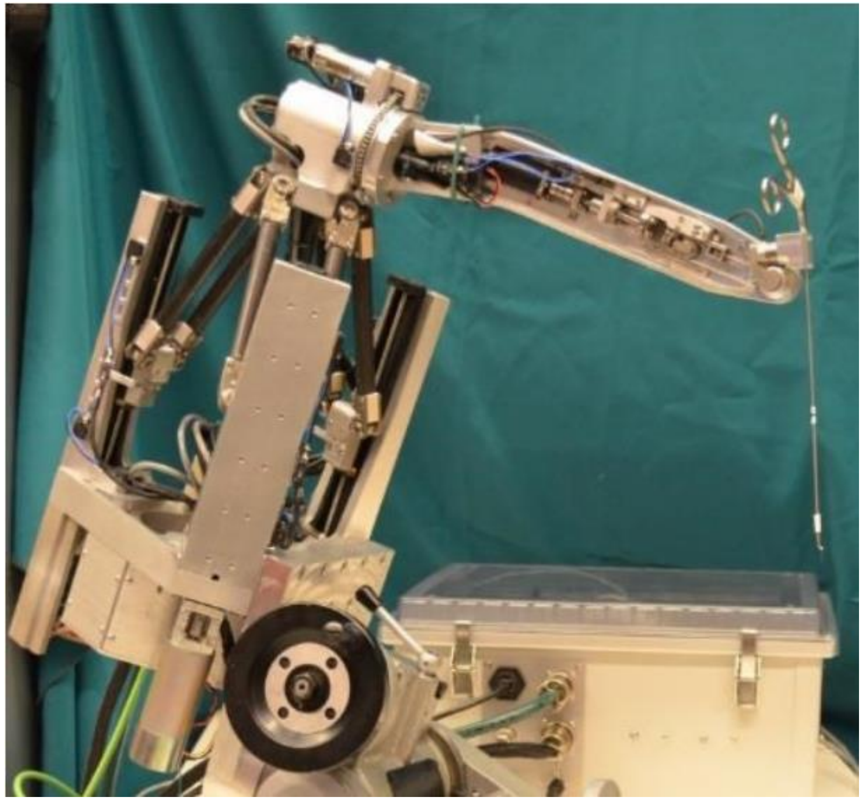
Project Goal

The goal of this project 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, while using the hand-over-hand control mode on the Galen Mk2, the tool feels reasonably weightless but this project aims to improve this ‘feel’ even further and make the robot more responsive to operator input.

Paper Selection

Kevin Olds's PhD Thesis

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

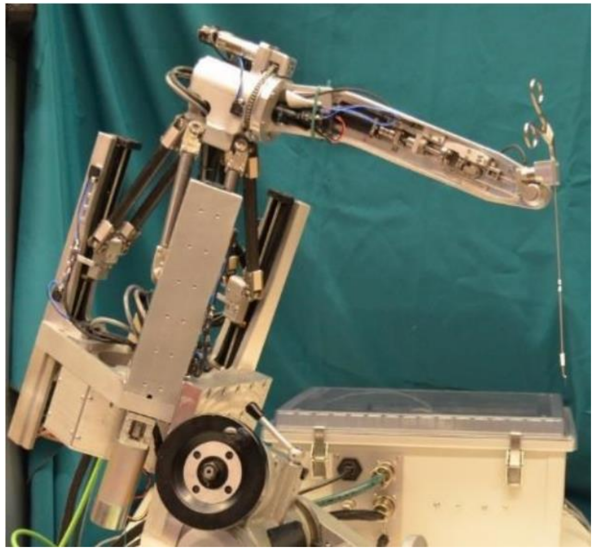


Hand-over-hand operation of REMS (Galen Mk0)

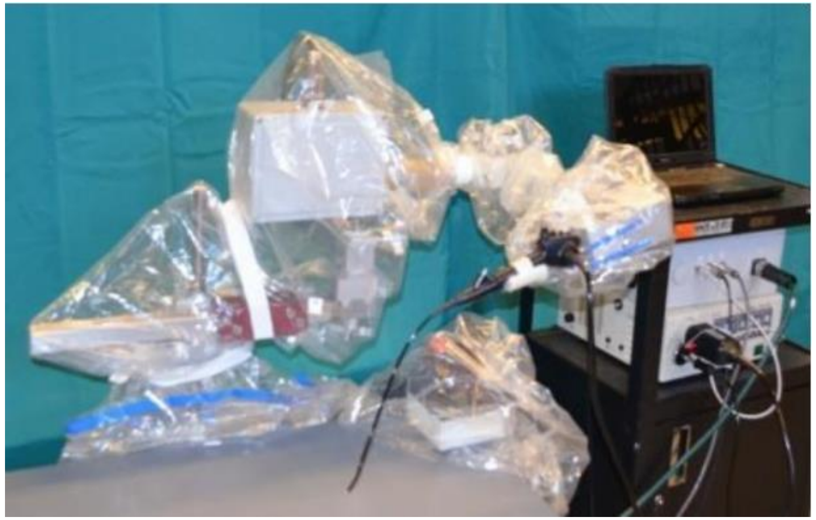
Image Credit:
[21] L. Akst, K. Olds, M. Balicki, P. Chalasani, and R. Taylor, "Robotic Microlaryngeal Phonosurgery: Testing of a "Steady-Hand Platform", Laryngoscope, vol. 128-, pp. 126-132, Jan., 2018. May 12 10.1002/lary.26621, PMID: 28498632

Paper Overview

Robotic ENT Microsurgery System:
Novel cooperatively controlled robotic system to address the precision and navigational challenges of OHNS



REMS



Robo-ELF

Robo-ELF Scope:
Proof of concept for a flexible endoscope controlled by a simple robot in laryngeal surgery and more.

Relevance to project

Current production Galen Mk3 and LCSR Galen 2.1 robot derived from REMS

This project has a heavy focus on the control system of the robot, thus a deep understanding of the logic and philosophy is necessary.

GALEN ROBOTICS

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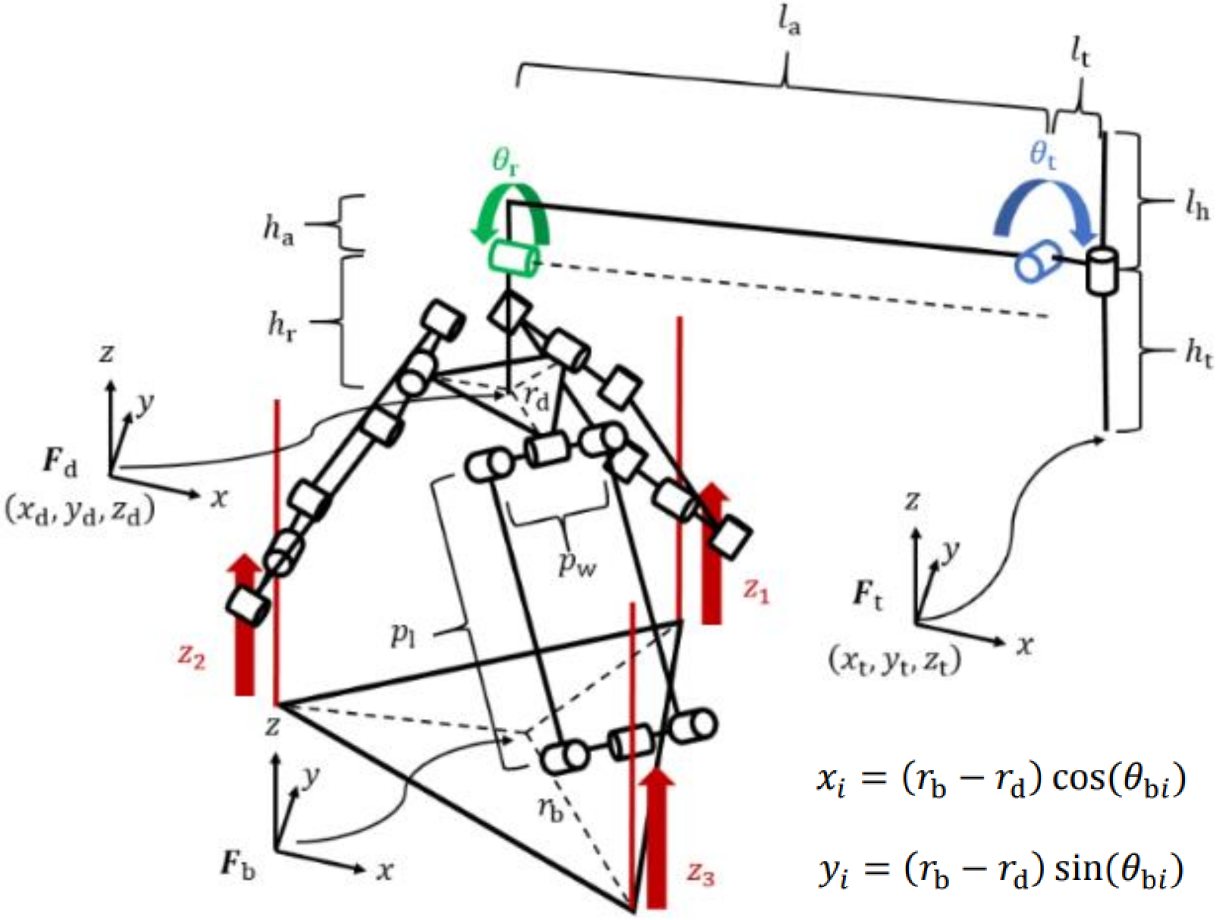
Topics Covered In Thesis

1. Overview of OHNS and surgical challenges
   - Ear surgery, sinus surgery, upper aerodigestive tract surgery, others
2. Robo-ELF
   - Requirements, design, validation
3. REMS design
   - Requirements, **design**, **kinematics**, hardware, **software**
4. REMS calibration and **validation**
   - Resolution, repeatability, stiffness, accuracy, laryngeal and suturing study
5. Future Work

REMS Construction & Kinematics

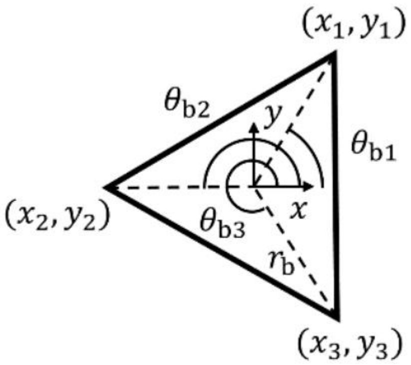


- 5dof Delta Robot
- Motors Located at the base
- Virtual RCM instead of physical

$$x_i = (r_b - r_d)\cos(\theta_{bi})$$

$$y_i = (r_b - r_d)\sin(\theta_{bi})$$

$$\theta_{bi} = (2i-1)\frac{\pi}{3}, i = 1, 2, 3$$



$$z_i = z_d - \sqrt{p_l^2 - (x_d - x_i)^2 - (y_d - y_i)^2}$$

Performance Indices

1. Manipulability

$$m = \sqrt{|JJ^{\mathrm{T}}|} = \prod_{i=1}^{n} \sigma_i$$

2. Inverse Condition Number

$$\kappa = \|J\|_2 \|J^{-1}\|_2$$

$$\kappa^{-1} = \frac{1}{\|J\|_2 \|J^{-1}\|_2} = \frac{\sigma_{\min}}{\sigma_{\max}}$$

1. Worst case velocity index

$$\mu_{\min} = \frac{v_{\mathrm{wc}}}{v_{\mathrm{j}}} \qquad \mu_{\min} = \min_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\dot{\boldsymbol{x}}\|_2 = \min_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\boldsymbol{J}\dot{\boldsymbol{\theta}}\|_2$$

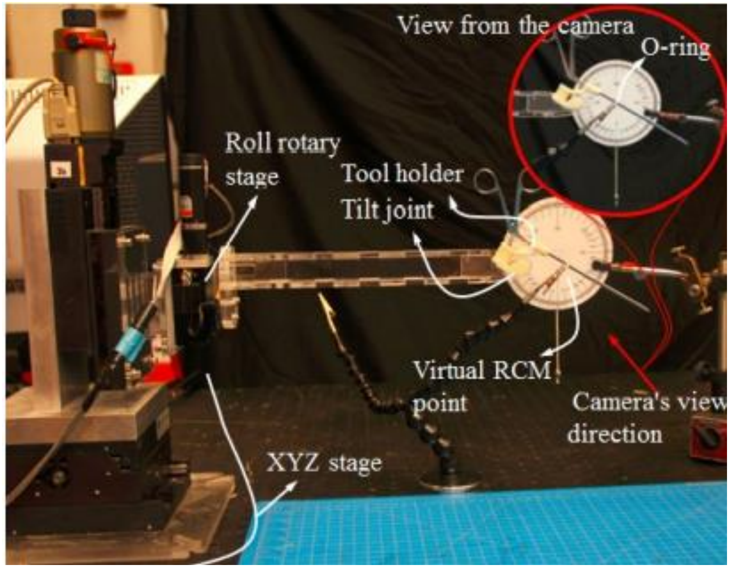
2. Worst case error index

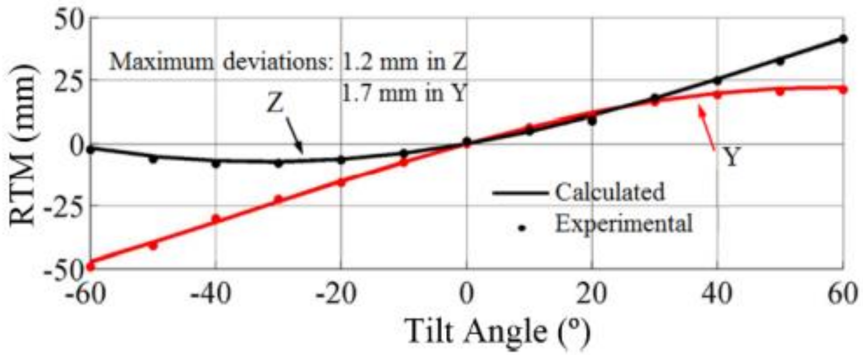
$$\mu_{\max} = \max_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\dot{\boldsymbol{x}}\| = \max_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\boldsymbol{J}\dot{\boldsymbol{\theta}}\|_2$$

3. New Isotropy index

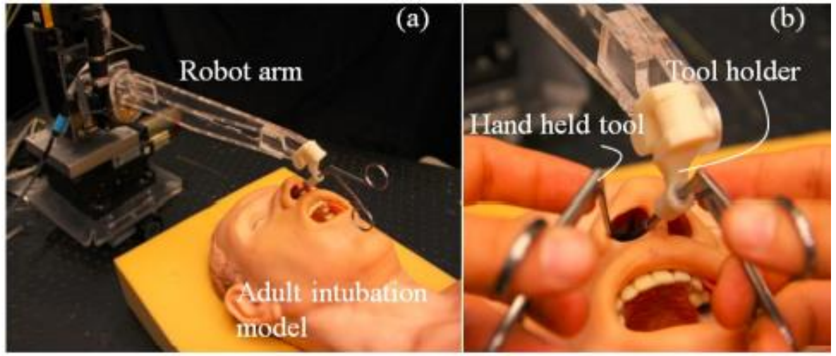
$$\iota = \frac{\mu_{\min}}{\mu_{\max}} = \frac{\min_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\boldsymbol{J}\dot{\boldsymbol{\theta}}\|_2}{\max_{\|\dot{\boldsymbol{\theta}}\|_\infty = 1} \|\boldsymbol{J}\dot{\boldsymbol{\theta}}\|_2}$$

Roll & Tilt Validation

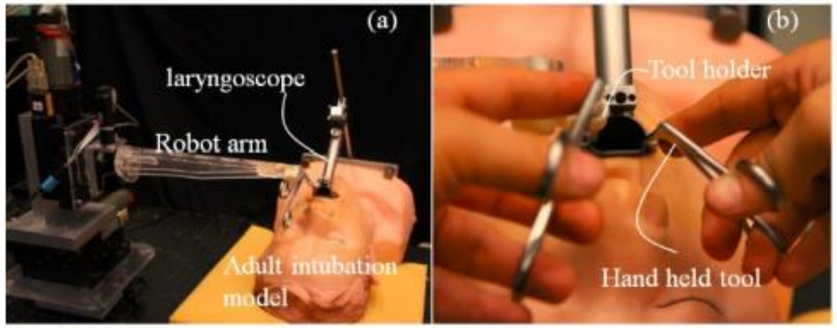




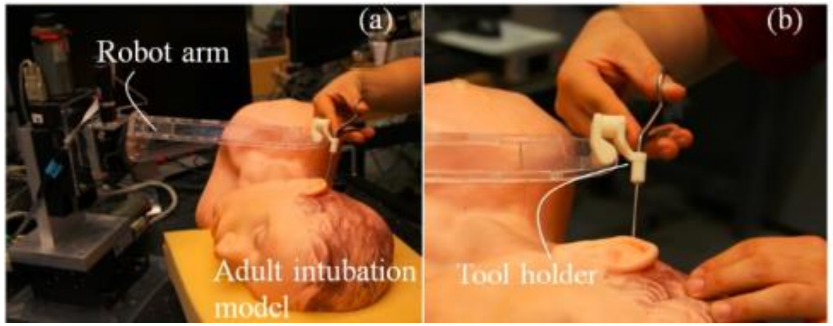
Roll & tilt stage RCM verification



Sinus surgery mockup



Laryngeal surgery mockup



Middle ear surgery mockup

Software: Admittance Control

Objective Function:

$$\underset{\Delta \boldsymbol{q}}{\operatorname{argmin}}(\|\boldsymbol{Gf} - \boldsymbol{J}\Delta\boldsymbol{q}\|)$$

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

$$\Delta\boldsymbol{x} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta roll \\ \Delta tilt \end{bmatrix}, \Delta\boldsymbol{q} = \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \\ \Delta roll \\ \Delta tilt \end{bmatrix} \quad \boldsymbol{f} = \begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_{roll} \\ \tau_{tilt} \end{bmatrix}$$

Gains Matrix:

$$\boldsymbol{G} = \begin{bmatrix} g_{1,1} & 0 & 0 & 0 & 0 \\ 0 & g_{2,2} & 0 & 0 & 0 \\ 0 & 0 & g_{3,3} & 0 & 0 \\ 0 & 0 & 0 & g_{4,4} & 0 \\ 0 & 0 & 0 & 0 & g_{5,5} \end{bmatrix}$$

$$g_{i,i} = p * m_{\mathrm{i}}^{f} \frac{\dot{x}_{\mathrm{i}}^{max} \Delta t_{opt}}{f_{\mathrm{i}}^{max}}$$

Constraints:

Joint Position Limits:

$$\Delta\boldsymbol{q}_l = \boldsymbol{q}_l - \boldsymbol{q}$$
$$\Delta\boldsymbol{q}_u = \boldsymbol{q}_u - \boldsymbol{q}$$

$$\Delta\boldsymbol{q}_l \leq \Delta\boldsymbol{q} + \boldsymbol{s}$$
$$\Delta\boldsymbol{q} - \boldsymbol{s} \leq \Delta\boldsymbol{q}_u$$
$$0 \leq \boldsymbol{s} \leq \boldsymbol{s}_b$$

Joint Velocity Limits:

$$\dot{\boldsymbol{q}}_{min}\Delta t_{opt} \leq \Delta\boldsymbol{q} \leq \dot{\boldsymbol{q}}_{max}\Delta t_{opt}$$

Workspace Position Limits:

$$\Delta\boldsymbol{x}_p = \boldsymbol{x} - \boldsymbol{x}_p$$

$$0 \leq \boldsymbol{n}_p \cdot (\Delta\boldsymbol{x}_p + \boldsymbol{J}\Delta\boldsymbol{q}) + s$$
$$0 \leq s \leq s_p$$

$$\underset{\Delta \boldsymbol{q}}{\operatorname{argmin}}(\|O(\Delta\boldsymbol{q}) + k(s)^2\|)$$

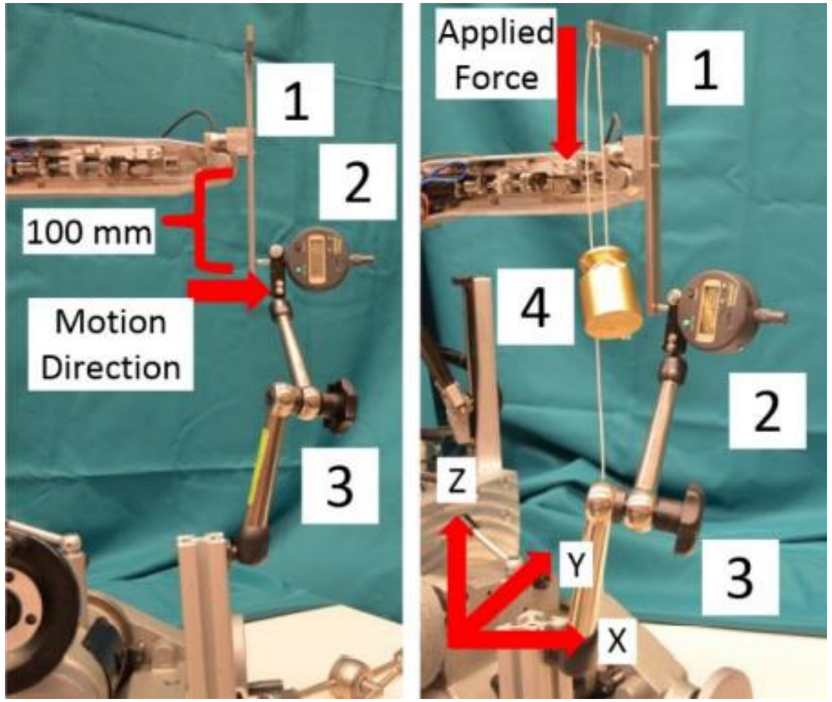
Workspace Velocity Limits:

$$\dot{\boldsymbol{x}}_{min}\Delta t_{opt} < \boldsymbol{J}\Delta\boldsymbol{q} < \dot{\boldsymbol{x}}_{max}\Delta t_{opt}$$

Overall Validation

Degree of Freedom	Resolution (mm)	Repeatability (mm)
X	0.003	0.077
Y	0.003	0.069
Z	0.002	0.018
Roll	0.005	0.099
Tilt	0.004	0.173
Worst-Case Total	0.011	0.302

	X Force	Y Force	Z Force
X Deflection (mm)	-0.610	0.020	0.287
Y Deflection (mm)	0.120	0.350	-0.242
Z Deflection (mm)	-0.250	-0.017	0.453



Test Setup

Critical Review

- Pros:
  1. Very thorough description of robot design & requirements
  2. Detailed context for robot usage, development and scope
  3. Demonstration of inadequacy of standard verification metrics and description of new metrics.
  4. Computational algorithms to calculate new metrics
  5. Surgical studies for validation
- Cons:
  1. Limited description of software implementation

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Questions

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