JOHNS HOPKINS
UNIVERSITY

Tool Gravity Compensation for the Galen Microsurgical System

Project Proposal

Team Members:
Adam Polevoy
Data Analysis Lead
apolevo1@jhu.edu

Parth Singh
Programming Lead
Psingh21@jhu.edu

Mentors:
Dr. Mahya Shahbazi
Dr. Russell Taylor

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Objective:

The objective of this project is to develop and validate models for tool gravity compensation and arm deflection for the Galen Surgical System. The gravity compensation model will be implemented for multiple tools for static and dynamic cases.

Background:

The Galen is a general purpose, hand-over-hand, admittance control robot developed mainly for otolaryngology. It is currently being commercialized by Galen Robotics inc, but was originally developed as PhD project in the LCSR and is still the subject of many research projects. The Galen reads values at a force/torque sensor and calculates the expected force/torque values at the user's point of contact on a tool. The tool then moves proportionally to the force exerted, allowing a surgeon to use a tool with the additional benefits of stability, tremor cancelation, and virtual fixtures. The force sensor, however, has no way distinguishing between the forces/torques exerted by the surgeon and those exerted by the tool itself. Currently the robot can cancel out values read at a particular moment, but rotating a tool results in new force/torque readings and often unintentional motion. The system also suffers from deflection issues, where the true position of the robot varies from the expected position because of flexibility in the joints.

Technical Approach:

1) <u>Static Compensation</u>

There are three models that our technical approach will employ, each increasingly complex. The first model is a simple static gravity compensation. The force and torque due to gravity can be represented as wrench vectors.

$$w_T = \begin{bmatrix} 0 & 0 & w & 0 & 0 & 0 \end{bmatrix}^T$$

$$w_b = \begin{bmatrix} 0 & 0 & b & 0 & 0 & 0 \end{bmatrix}^T$$

ω_T is the wrench on the tool due to gravity. ω_B is the wrench on the tool adaptor, as well as other non-tool components that could affect the force sensor, due to gravity. ω and b are the weights of the tool and other attached components, respectively. These are both in a global frame. The rotation matrix between the sensor and this global frame (the tool frame) can be calculated as:

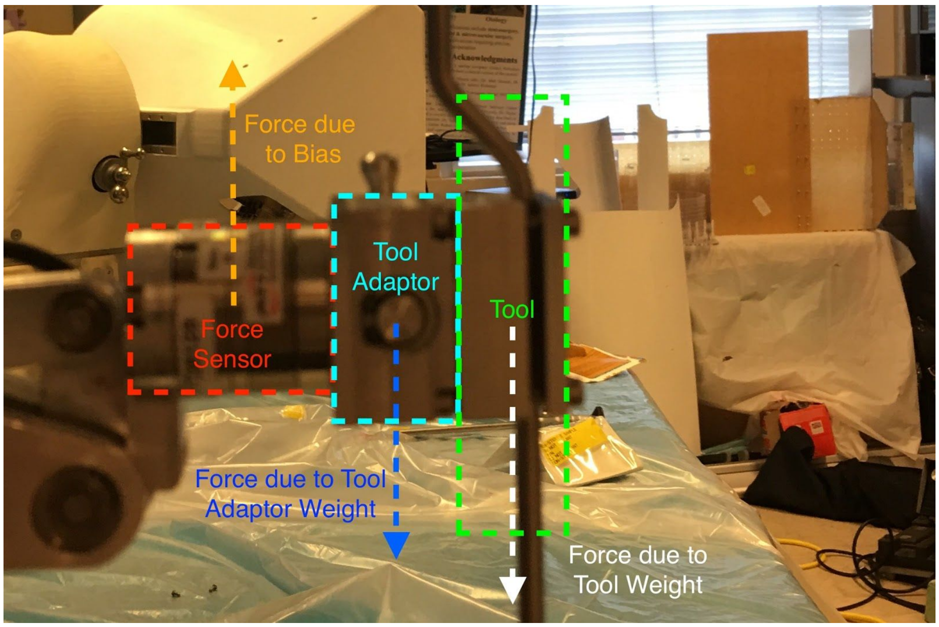
$$R_S = R_z(z_{off})^T * R_y(y_{off})^T$$

$$R_{ST} = R_S * R_y(\theta_{tilt})^T * R_x(\theta_{roll} - \theta_{off})^T$$

R_s is the rotation of the force sensor on the robot without any roll or tilt. R_{ST} is the rotation of the force sensor on the robot when you take roll and tilt into account. Assuming that the force sensor is re-biased when $R_S = R_{ST}$ (when there is no roll or tilt) and when the tool is not attached, the wrench at the sensor can be calculated as:

$$w_S = \begin{bmatrix} R_{ST} & 0 \\ -R_{ST}\hat{p_T} & R_{ST} \end{bmatrix} (w_T + w_b) - \begin{bmatrix} R_S & 0 \\ -R_S\hat{p_T} & R_S \end{bmatrix} w_b$$

$\widehat{p_T}$ is the skew matrix of the tool center of mass position vector with respect to the sensor. ω_s is the predicted wrench in the force sensor frame. The first term is the wrench on the force sensor due to the total weight of the tool and other components affecting the force sensor. The second term subtracts out the bias on the force sensor, assuming the rebias condition stated above.



At this point, ω_s will be a vector of equations with unknown parameters, which would include tool mass and center of mass. For each of these, the parameters can be regressed given enough data using simple least squares:

$$\vec{w}_{S_i} = \mathbf{A}_i \vec{b}_i$$

$$\vec{b}_i^* = (\mathbf{A}_i^T \mathbf{A}_i)^{-1} \mathbf{A}_i^T \vec{w}_{S_i}$$

ω_{s_i} contains output data for each wrench element, A_i contains input data in the form of products of sinusoidals of joint angles, and b_i^* contains the ideal parameters.

The predicted force sensor wrench can then be subtracted from the measured wrench to create a compensated value

$$w_{comp} = w_{meas} - w_S$$

ω_{comp} is the compensated wrench, and ω_{meas} is the measured wrench.

2) <u>Dynamic Compensation</u>
Dynamic compensation will have one difference: the tool wrench vector will be calculated using the Lagrangian, thus taking into account dynamic motion:

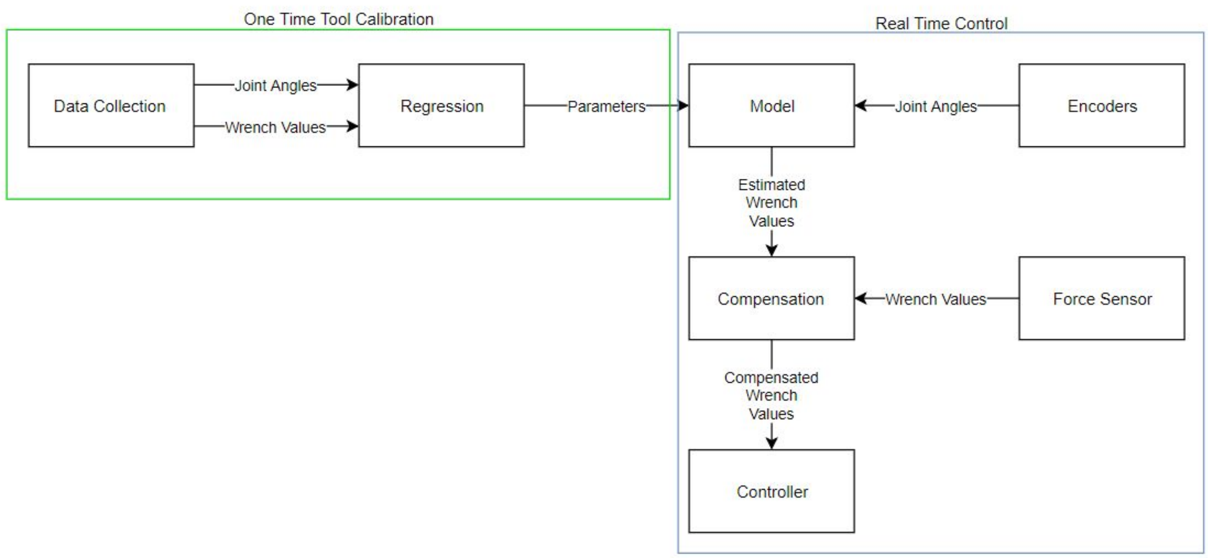
$$L = KE - PE$$

$$w_T = \frac{\partial}{\partial t}(\frac{\partial L}{\partial \dot{x}}) + (\frac{\partial L}{\partial x})$$

$$w_T = M(x) + C(x, \dot{x}) + G(x)$$

L is the Lagrangian, KE is the kinetic energy, PE is the potential energy, x represents generalize coordinates, $M(x)$ is the mass matrix term, $C(x, \frac{d}{dt}x)$ is the velocity-product term, and $G(x)$ is the gravity term. This will, of course, make the resulting equations for the force sensor wrench vector more complicated, and there may be more parameters to regress. Otherwise, the following steps are the same as in static compensation.

Once these models have been developed, our gravity compensation system can be represented as a block diagram.



3) <u>Deflection Characterization</u>

Lastly, we will build a model of arm deflection in the system due to forces and position applied to the tool at the robot end-effector. We will first create a CAD model for a tracker tool that can be attached to the new tool adaptor used on the Galen system. This will be 3D printed and tracker bodies will be attached.

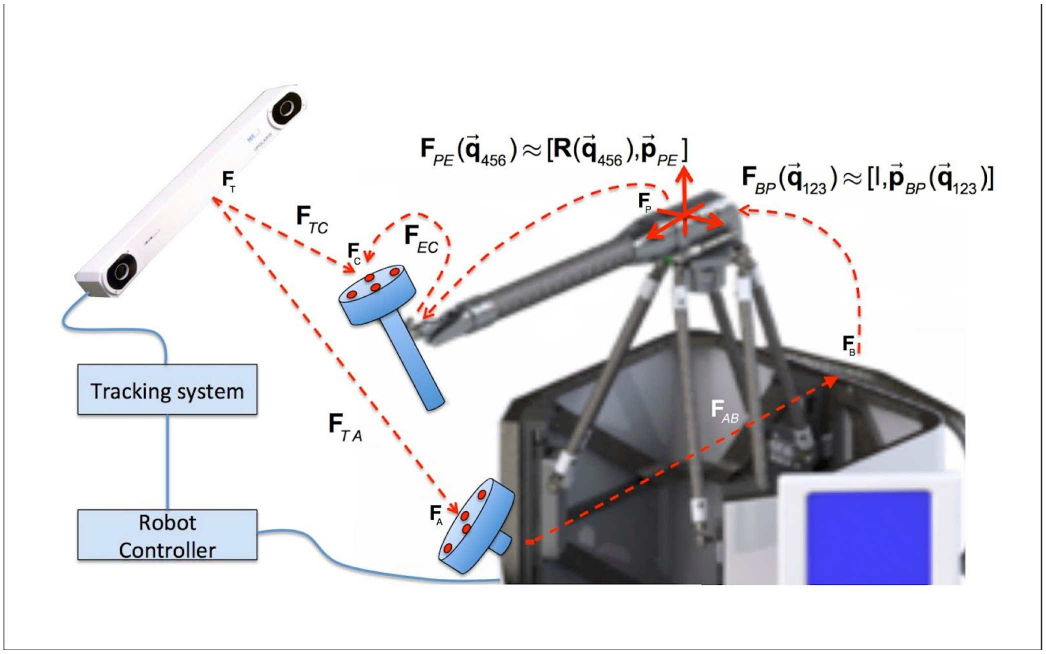


Image Credit: CIS 1 2018 homework 4

We begin by finding the frame transformations shown in the image above. F_{BP} and F_{PE} for a given position can be calculated using the Galen forward kinematics. F_{EC} is a static displacement that will be determined from the tracker tool CAD model and will be verified. F_{TC} and F_{TA} will be reported by the Optical Tracking System. F_{AB} can be found by assuming no deflection at the home position with no force and calculating

$$F_{AB} = F_{TA}^{-1} F_{TC} F_{EC}^{-1} F_{PE}^{-1} F_{BP}^{-1}$$

We then move the robot to various positions within the workspace and apply forces in different directions, recording force sensor data, joint angles, tool position as reported by the robot, and tool position as measured by an optical tracker. We calculate the expected position using

$F_{BP} F_{PE} F_{EC}$ and the actual position using $F_{AB}^{-1} F_{TA}^{-1} F_{TC}$.

After collecting this data and doing the calculations above, we will develop a model to predict the deflection values at a location using a shallow neural net. We will attempt different configurations and document the performance of each. Parameters that we will change will include the number of layers, activation function, and loss function.

Deliverables:

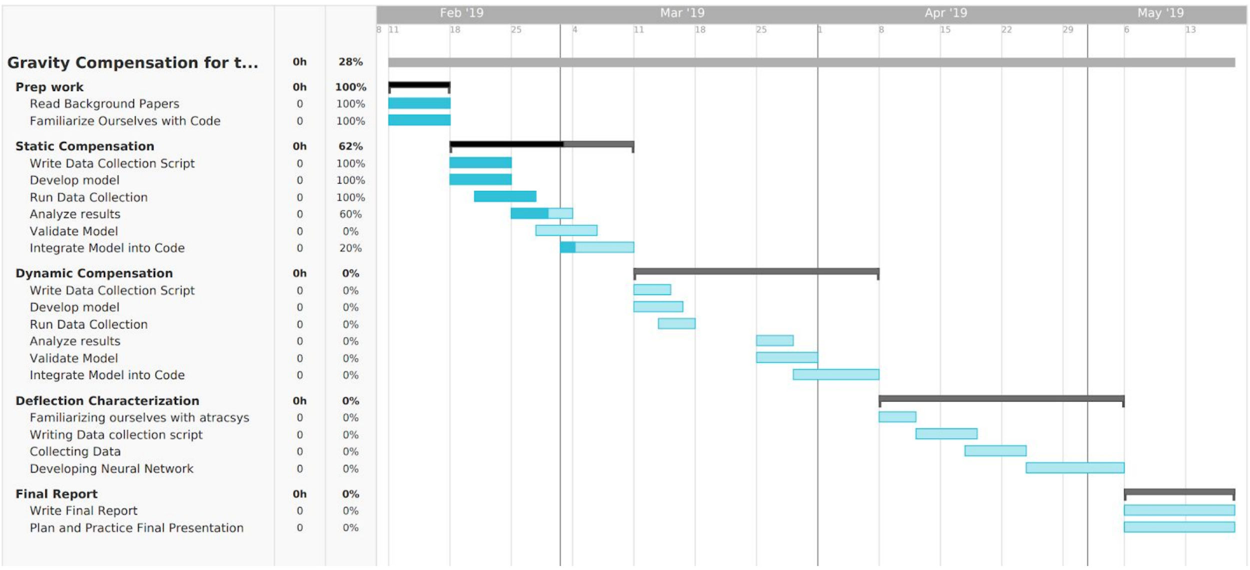
- Minimum:
  - Report with data and analysis demonstrating a model capable of predicting 6 DoF forces and torque given a tool and tool holder pose due to gravity, along with code and documentation
  - Video and data demonstrating successful integration of gravity compensation into robot control software, along with code and documentation
- Expected:
  - Report demonstrating a model capable of predicting 6 DoF forces and torque given a tool and tool holder pose due to dynamic motion, along with code and documentation
  - Video and data demonstrating successful integration of dynamic model compensation into robot control software, along with code and documentation
- Maximum:
  - Report demonstrating a model capable of predicting deflection forces at any point in the Galen workspace.

Dependencies:

Dependencies	Solution	Alternative	Date	Status
Access to Mock OR	Fill out paperwork	N/A	N/A	Resolved
Access to Galen Mark 2	Speak with Galen Commercial team about scheduling	Use Galen Mark 1.	2/14	Resolved
Access to Galen Bitbucket Repository	Email Barry Voorhees	Speak to Galen Team/Dr. Taylor. Worst Case, use old LCSR repo and mark 1	2/14	Resolved
Get access or knowledge about previously used data collection on the Galen	Email Paul Wilkening	Read through code and write our own script.	2/14	Resolved
Discuss tool exchange	Speak with Dave Levi	Use Galen Mark 1	2/14	Resolved
Login Access to Galen Computers	Resolved	N/A	N/A	Resolved
Access to atracsys optical tracker	Email Dr. Taylor	Ask Dr. Taylor about alternative optical trackers	4/1	Resolved
Access to 3d Printer for tracker tool	Speak with Dave Levi about LCSR printer	Speak with Dr. Taylor about funds for Wyman printer	4/1	On-going

Access to tracker bodies	Speak with Galen Team	Use Micron tracker and print out trackers	4/1	On-going
Google Cloud Compute Credits	Email Dr. Taylor	Use our laptops to train neural nets	4/1	On-going

Schedule:



Milestones:

• Functional Data Collection Script	February 22nd
• Functional Static Prediction Model	March 4th
• Integrated Static Compensation	March 11th
• Functional Dynamic Prediction Model	April 1st
• Dynamic Compensation Integrated	April 8th
• Deflection Data Collected	April 22th
• Functional Deflection Model	May 4th
• Final Report/Presentation	May 16th

Management Plan:

We plan to meet and work on Tuesdays, Thursdays, and Fridays from 8:45-11:45am to work. We have weekly mentor meetings scheduled with Dr. Shahbazi at 10am on Fridays. Code changes will be stored in a branch of the Galen research repository. Data and reports will be stored on JHBox.

Reading List:

Beer, Randall F., et al. "Development and evaluation of a gravity compensated training environment for robotic rehabilitation of post-stroke reaching." *Proc. 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 2008.

D. A. Fresonke, E. Hernandez and D. Tesar, "Deflection prediction for serial manipulators," *Proceedings. 1988 IEEE International Conference on Robotics and Automation*, Philadelphia, PA, USA, 1988, pp. 482-487 vol.1.

Dimeas, Fotios & Aspragathos, Nikos. (2015). Learning optimal variable admittance control for rotational motion in human-robot co-manipulation. IFAC-PapersOnLine. 48. 10.1016/j.ifacol.2015.12.021.

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Kim, Woo Young & Han, Sanghoon & Park, Sukho & Park, Jong-Oh & Ko, Seong Young. (2013). Tool Gravity Compensation for Maneuverability Enhancement of Interactive Robot Control for Bone Fracture Reduction System.

Lehmann , Tavakoli, Usmani, and Sloboda, “Force-Sensor-Based Estimation of Needle Tip Deflection in Brachytherapy,” Journal of Sensors, vol. 2013, Article ID 263153, 10 pages, 2013.

Luo, Ren C., Y. Yi Chun, and Yi W. Perng. "Gravity compensation and compliance based force control for auxiliarily easiness in manipulating robot arm." *Control Conference (ASCC), 2011 8th Asian*. IEEE, 2011.

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