Kinematic Simulation, Calibration, and Accuracy Improvement for the Galen Robot

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Background & Motivation

The Galen Platform (Figure 1) is a family of hand-over-hand, collaborative robots developed in the Johns Hopkins Laboratory for Computational Sensing and Robotics. Intended for hand tremor cancellation in a broad range of surgical procedures, it is currently being commercialized by Galen Robotics, a robotics start-up company in Baltimore, MD.

Galen features a custom five degree of freedom architecture, and covers the footprint of about one person in the operating room. A wide variety of tools can be attached to the Galen for the surgeon to operate with such as pointers, drills, and forceps. While the surgeon operates with these tools, the Galen steadies their hand and cancels any tremor which can complicate the surgical procedure. (Figure 2)

Figure 1: Full assembly of the Galen Mk. 2 platform [1]

Since it is intended to help with delicate movement such as tremor, and since the nature of surgical operations is sensitive with very small error tolerances, the Galen platform needs to be a high precision and accuracy robot, which calls for an accuracy assessment and kinematic calibration for improvement. In addition to calibrating the real-world robot, a virtual simulation of the Galen robot would be beneficial for testing and debugging control software, kinematic and dynamic parameters, and trajectories by providing a safer and much more available and duplicable environment for experimentation. Hence, this project aims to first create such a simulation for the robot and then to calibrate the real-world robot for improved accuracy.

Figure 2: Galen and surgeon cooperating while drilling a mastoid bone[2]

In light of this, our project goals are to:
(1) Successfully model the kinematics and dynamics of the Galen in a simulation environment
(2) Calibrate the Galen to improve tool tracking accuracy

Technical Approach

Simulation: The Galen simulation will be an environment where employees and research affiliates can manipulate a physically accurate model of the Galen platform. The simulation will be developed in Blender animation studio and will utilize the Asynchronous Multi-Body Framework (AMBF) software package, an open source toolbox for real-time dynamic modeling of rigid bodies. Users will interact with the simulated robot via a custom Python client, a modified version of the template client provided in the AMBF GitHub repository. Galen Robotics will provide 3D mesh files of the robot that will be imported into the simulation environment. If time permits, we will document a series of video tutorials explaining how to use the Galen simulation; we intend for these tutorials to be used by the Galen commercial and research teams to further develop the platform.

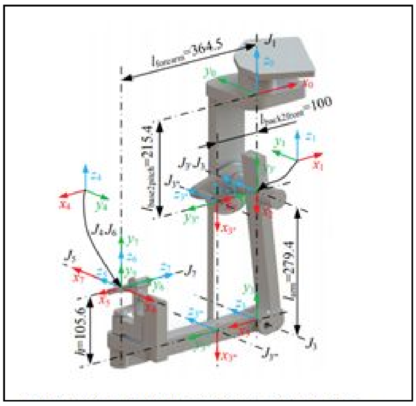

Figure 3: Sample virtual model of the dVRK MPMs representing its 3D geometry, kinematics, and dynamic properties [3]

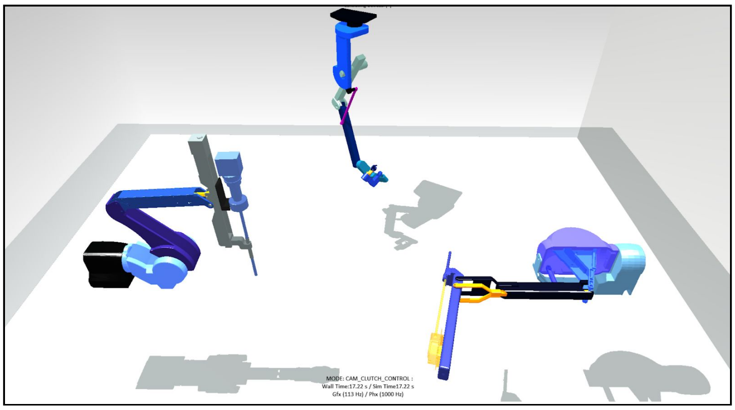

Figure 4: Multiple virtual robot models in the simulation environment [4]

Calibration: Calibration testing will allow us to generate an error correction function to match actual with expected tool position/orientation. This stage of the project largely depends on the completion of the Galen simulation as the simulation will be used to model an idealized calibration experiment. The only calibration-related tasks we aim to complete in parallel with the simulation are learning to use the Galen research software interface and developing the necessary protocol, fixtures, and data analysis scripts for the calibration test. After the simulation is complete, we will perform calibration testing, use the data to generate the correction function, and then test the Galen with the correction function. Part of our project evaluation will be a measure of the error between the new, corrected tool location and the desired kinematic input. If time permits, we will work with the Galen team to integrate the correction function into the commercial software package and test the newly-corrected tool accuracy with virtual fixtures.

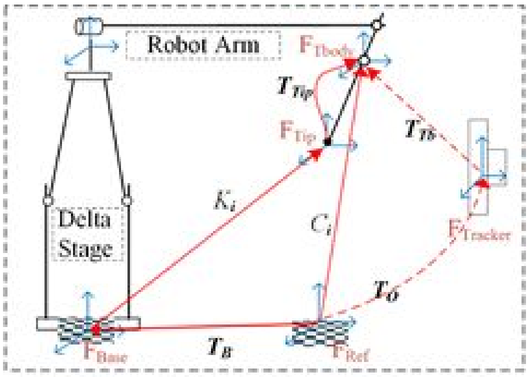

Figure 5: Coordinate frames of the REMS robot (without distortion) to perform calibration between [1]

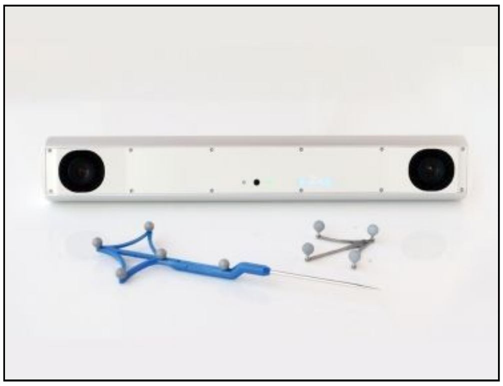

Figure 6: Sample optical tracking device that can be used for kinematic calibration [5]

Overview of Deliverables with Deadlines

Minimum Deliverables:

- Galen robot simulation developed (13 March 2020)
- XYZ (base) calibration (17 April 2020)
- Accuracy assessment after calibration (24 April 2020)
- Demonstration by controlling the end effector and assessing accuracy (5 May 2020)

Expected Deliverables:

Minimum deliverables, plus...

- Wrist calibration (24 April 2020)
- Accuracy assessment after calibration (24 April 2020)

Maximum Deliverables:

Expected deliverables, plus...

- Galen robot simulation tutorials (1 May 2020)
- Integration of XYZ and wrist calibration into research software (1 May 2020)
- Demonstration with virtual fixtures (5 May 2020)

Management Plan

Meetings:

- Weekly meeting with Dr. Adnan Munawar, Max Li, Henry Phalen: Monday 10-11 am.
- Weekly meeting between Nico and Can: Thursday 10:30 - 11:30 am. Go over and report on individual responsibilities, start group tasks together.
- Can and Nico will meet as necessary every week to complete further tasks together.
- Additional individual meetings with either Adnan, Max, or Henry when their assistance is needed based on availability

Documentation & Asset Management:

- Everything done using Blender and AMBF will be recorded in OBS Studio and transcribed.
- Files and code for AMBF stored on shared (private) Google Drive folder
- Galen interface code and assets kept on personal devices and agreed on cloud (Azure), or git.
- Documentation of code will be integrated into individual code files as comments and README files, and will be put together on a separate report.

Dependencies, Tasks, and Timeline

Table 1 lists our dependencies while Table 2 lists the tasks needed to complete in order to successfully complete our milestones and deliver what we envisioned with our mentors. Figure 7 shows the tasks' dependence on each other and Figure 8 shows the proposed timeline to work on and complete said tasks in consideration of other tasks dependencies.

Table 1: List of Dependencies

Date Needed	Dependency	Details	Solution	Status	Contact for Help	Alternatives
02/ 14	Galen Kinematic Parameters, CAD files (Mk. 1 and Mk. 2)	Parameters to model the robot in simulation	Ask Dave Levi for kinematic parameters/CAD	In progress: expected by 02/26	Dave Levi	No alternatives
Late March - April	The Galen Robot (Mark 1 & 2) Availability	The robot, with working forward kinematics	Work with Galen team to figure out robot availability	Complete: BUT need to confirm for specific time and date	Max Li, Galen people	We can use Mark 1 if Mark 2 is unavailable
03/14	Galen Python Interface	Interface required to control the robot, in Python	Ask Florin and Max for access and tutorial	Incomplete	Dr. Taylor, Florin Neascu	No alternatives
03/22	Calibration Equipment	Optical tracking system, fiducials (Atracsys)	Find instructions necessary software & make sure we have necessary connections	In progress: Anna & Dave setting it up for another project	Anna Goodridge, Max Li, Dave Levi	Another optical system in the LCSR

Table 2: Milestones and Tasks to Complete

Task Start Date	Task End Date	Tasks	Dependency & Prerequisites	Milestone Deadline	Milestone	Contact for Help
02/13	03/02	A. Modeling robot in Blender	Galen STL & kinematic parameters	03/06	1.Galen model working in AMBF	Dr. Munawar
02/13	03/02	B. Learning to use AMBF package (write control script)	-			Dr. Munawar
03/02	03/13	C. Run simulation experiment	Task A,B	03/13	2.Galen Simulation runs and can be used to check trajectories	Dr. Munawar
02/26	03/27	D. Learning to run Galen software interface	Galen interface & robot	04/06	3.Calibration data (pose error) acquired	Max Li, Kevin Gilboy
03/13	04/01	E. Develop real-world calibration experiment and evaluation method	Task C, Calibration equipment, Galen robot			Anna Goodridge, Max Li, Henry Phalen
04/01	04/06	F. Perform calibration experiment	Task D, Calibration equipment, Galen interface & robot			Max Li, Henry Phalen
04/06	04/17	G. Use Experimental data to get correction function	Task F	04/17	4.Experimental correction function calculated	Max Li, Dr. Taylor
04/17	04/24	H. Test Galen robot with correction function	Task G, Calibration equipment, Galen interface & robot	04/24	5.Experimental data showing reduced pose error	Max Li, Dr. Taylor
04/24	05/01	*I. Galen Robot Simulation Tutorials (if time allows)*	Task A,B,C	05/01	6.Tutorials online on AMBF Wiki	Dr. Munawar
04/24	05/01	*J. Integration into research software (if time allows)*	Task H, Galen interface & robot	05/01	7.Correction function integrated into Galen research SW	Max Li, Kevin Gilboy, Florin Neascu
04/24	05/05	K. Prepare demo: Moving Galen or *Virtual Fixtures (if time allows)*	Task H, Galen interface & robot	05/05	8.Working demo with Galen Robot	Max Li, Henry Phalen

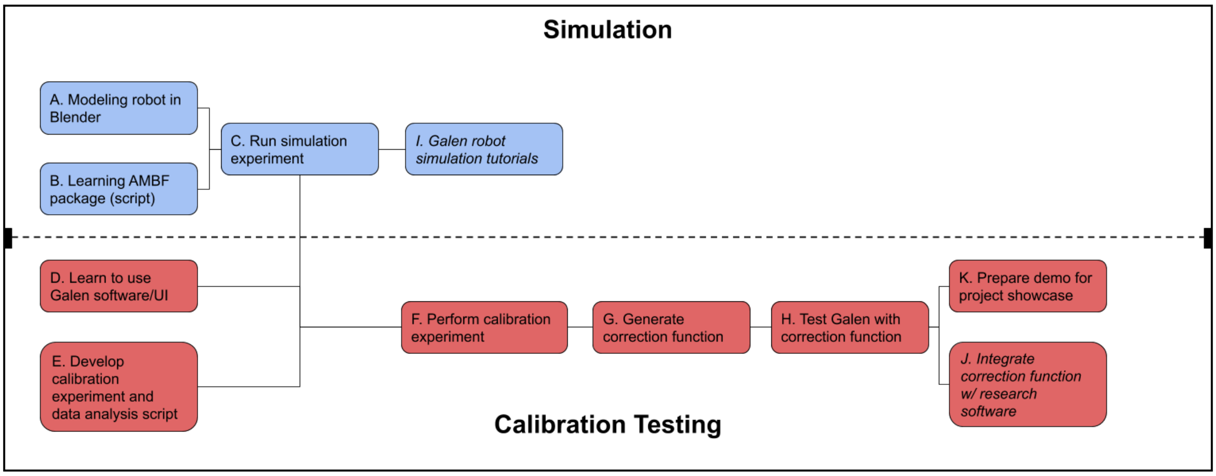

Figure 7: Workflow diagram showing specific task dependencies

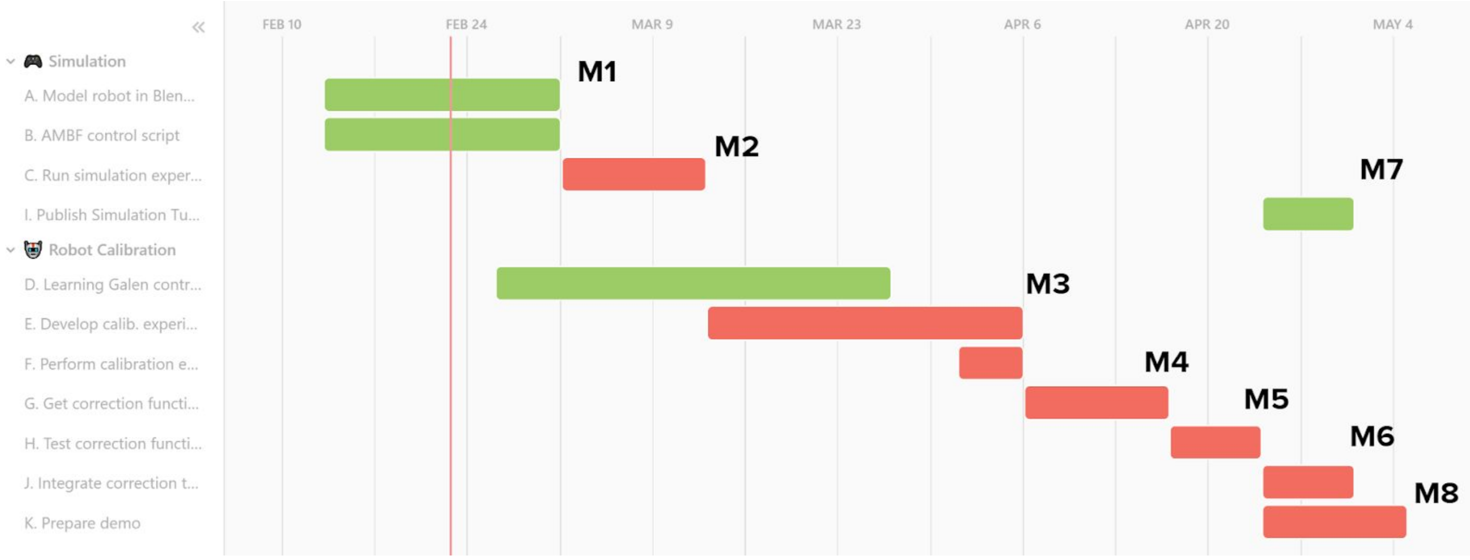

Figure 8: Gantt Chart of Proposed Timeline
Key: active items are green and items pending start are red

Reading List

The following is a tentative list of papers to be read over the semester for technical insight into surgical robot calibration and evaluation. This list might change as the project evolves; more might be added or some might be replaced with others.

[1] K. C. Olds, *"Robotic Assistant Systems for Otolaryngology - Head and Neck Surgery"*, Ph.D Thesis, The Johns Hopkins University, 2015

[2] L. Feng, P. Wilkening, Y. Sevimli, M. Balicki, K. C. Olds, and Russell H. Taylor, *"Accuracy Assessment and Kinematic Calibration of the Robotic Endoscopic Microsurgical System"*, in IEEE Engineering in Medicine and Biology Conference (EMBC), Orlando, Aug. 16-20, 2016. pp. 5091-5094.

[3] C. He, K.C. Olds, I. Iordachita, and R. H. Taylor, *“A new ENT microsurgery robot: error analysis and implementation”,* in Proc. IEEE Int. Conf. on Robotics and Automation (ICRA), 2013, pp. 1221-1227.

[4] M. Shah, R. D. Eastman, and T. Hong, *“An overview of robot-sensor calibration methods for evaluation of perception systems,”* in ACM Proceedings of the Workshop on Performance Metrics for Intelligent Systems, 2012, pp. 15-20

[5] J. Wang, C. Wu and X. Liu, *"Performance Evaluation of Parallel Manipulators: Motion/Force Transmissibility and its Index,"* Mech. Mach. Theory, vol. 45, no. 10, pp. 1462-1476, 2010.

[6] C. Wu, X. Liu and J. Wang, *"Force Transmission Analysis of Spherical 5R Parallel Manipulators,"* in ASME/IFToMM Int. Conf. Reconfigurable Mech. and Robots, London, UK, 2009.

[7] G. Boschetti and A. Trevisani, *"Direction Selective Performance Indexes for Parallel Manipulators,"* in 1st Joint Int. Conf. Multibody System Dynamics, Lappeenranta, Finland, 2010.

[8] K. Olds, P. Chalasani, P. Lopez, I. Iordachita, L. Akst and R. H. Taylor, *"Preliminary Evaluation of a New Microsurgical Robotic System for Head and Neck Surgery,"* in IEEE IROS, Chicago, 2014.

References

[1]: Taylor, *”Kinematic Calibration and Improved Accuracy for Galen Robot”,* CIS II, 2/2/2020, Baltimore
[2]: Taylor, *”Guided Bone Cutting for Robot Assisted Neurosurgery”,* CIS II, 2/4/2020, Baltimore
[3]: Munawar, “*Improving Haptic Feedback of dVRK MTMs”*, 2/4/2020, CIS II, Baltimore
[4]: https://github.com/WPI-AIM/ambf/wiki/Controlling-dVRK-Manipulators
[5]: https://www.medicalexpo.com/prod/atracsys/product-100844-713103.html