# Transparency Optimization of the Galen Surgical System with a Frequency Domain Admittance Controller Design

# Check Point

**Students:** Brevin Banks

**Mentors:** Ugur Tumerdem, Manish Sahu, Adnan Munawar, Mohammad Salehizadeh, Russell Taylor

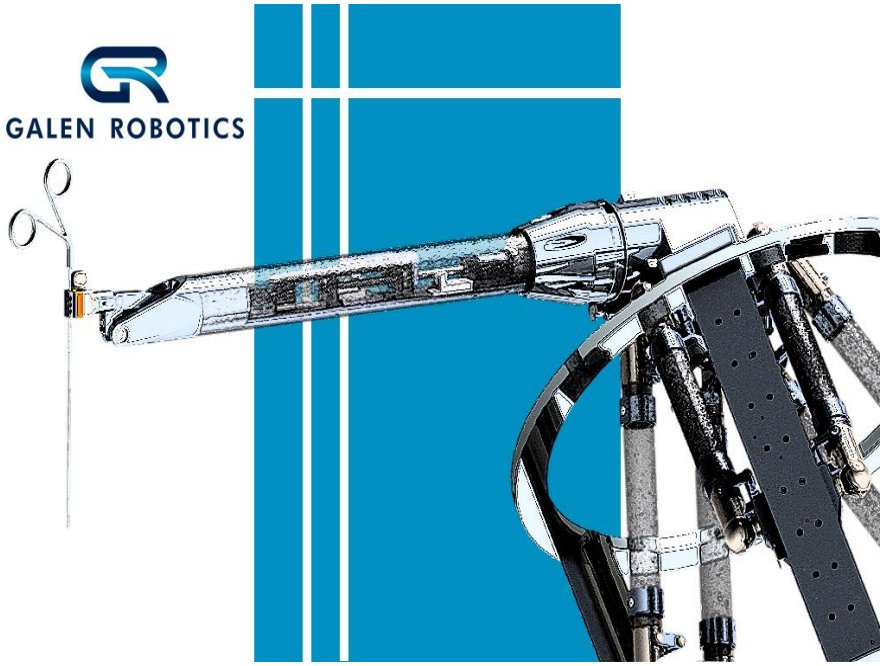
# Project Review & Significance

The hand over hand guidance cobot in the mock OR, the Galen Robot, is used to assist surgeons in ENT microsurgery. It assists by restricting motion through virtual fixtures and allows for steady, accurate surgeries to be performed.

In order for the surgeon to feasibly and comfortably use the device it must be what we call **stable** and **transparent.** And the current controller could be better optimized for these two variables.

Stability is achieved through observing the forces, velocities, etc. on the input and ensuring the output is bounded and behaves as predicted. (ie. No vibrations or dangerous motions)

Transparency is achieved through control schemes that measure the input human force and try to react by removing some of the impedance or resistance that would naturally be felt by the robot dynamics and actuators.




Democratizing Robotic Surgery and Microsurgery. Galen Robotics. (2022, November 15). Retrieved February 13, 2023, from https://www.galenrobotics.com/

# Previous Deliverables

**Minimum:**

- A stable frequency domain admittance controller in MATLAB code for the Galen surgical robot in the AMBF simulation environment
- A simulated control system package with optimized transparency containing code files that can be used in AMBF and MATLAB and is transferable to hardware

**Expected:**

- An applied control system package to the low-level Galen controller that is stable and optimized for transparency including virtual fixtures
- A validated objective improvement in transparency according to specified metrics

**Maximum:**

- A completed user study to investigate subjective transparency preference with different controllers on the Galen robot

# Summary of the Efforts to Now

- Verified Stable and Transparent Mass Spring Damper Simulations
- Galen robot controller in AMBF through MATLAB
- Simulated System Identification
- Application of Admittance controller in AMBF simulation
- *Starting Real Robot System Identification

# Mass Spring Damper Simulations

- Mimic Mass Spring Damper Admittance control designs from the literature with the basic feedback controller design

*Admittance*

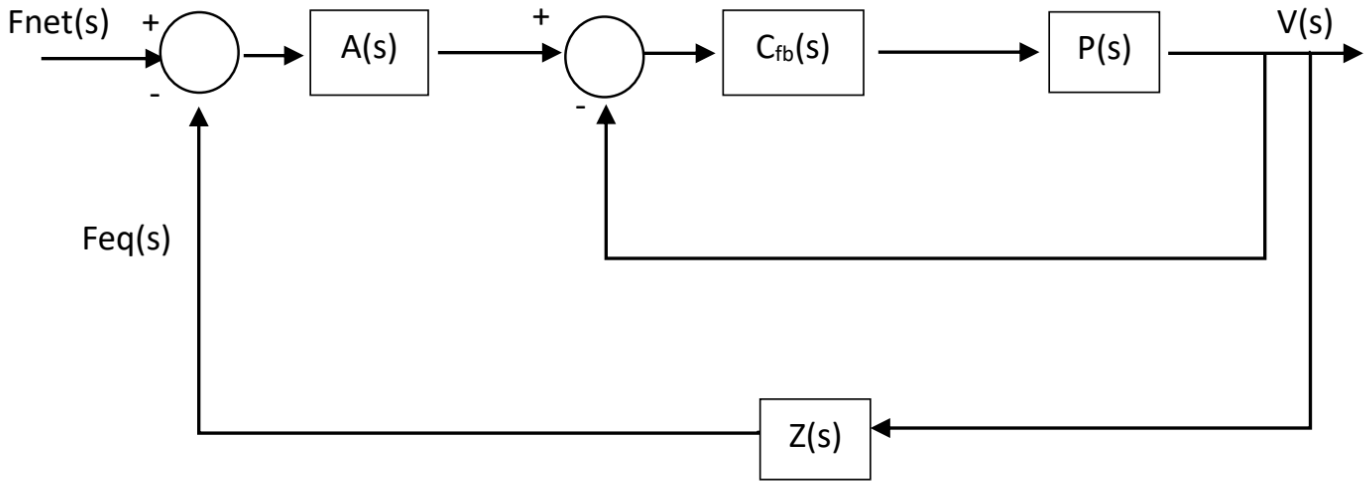
$$A(s) = \frac{1}{m_{ad}s + b_{ad}}$$

*Plant*

$$P\ (s) = \frac{s}{ms^2+bs+k}$$

*Impedance*

$$Zeq(s) = mhs^2 + bhs + \frac{kh}{s} + \frac{ke}{s}$$

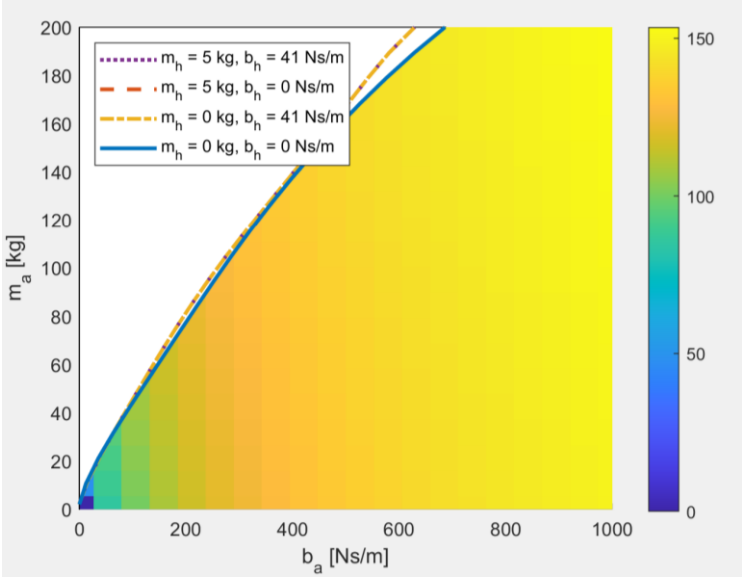



$$T(s) = \frac{V}{F} = \frac{AC_{fb}P}{1+C_{fb}P(AZ+1)}$$

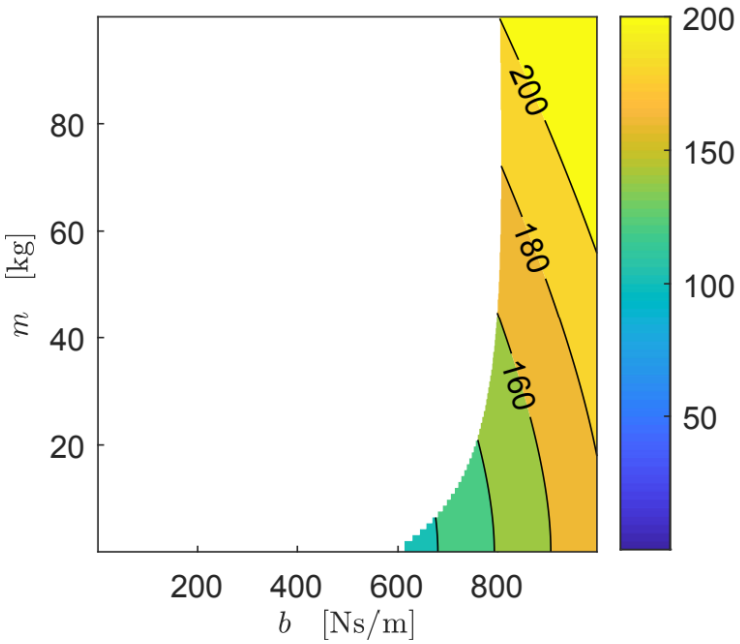
# Mass Spring Damper Simulations: Unsuccessful Results

- Ensure this optimization admittance approach was feasible for guaranteeing stability and improved transparency
- Unable to replicate work of Aydin et al. Lacking in depth stability analysis and their system identification method was unclear

**Ours**



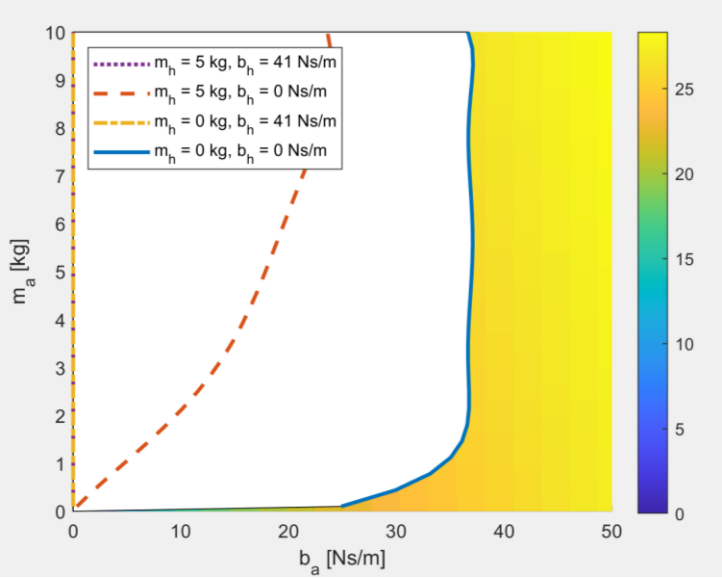

**Theirs**



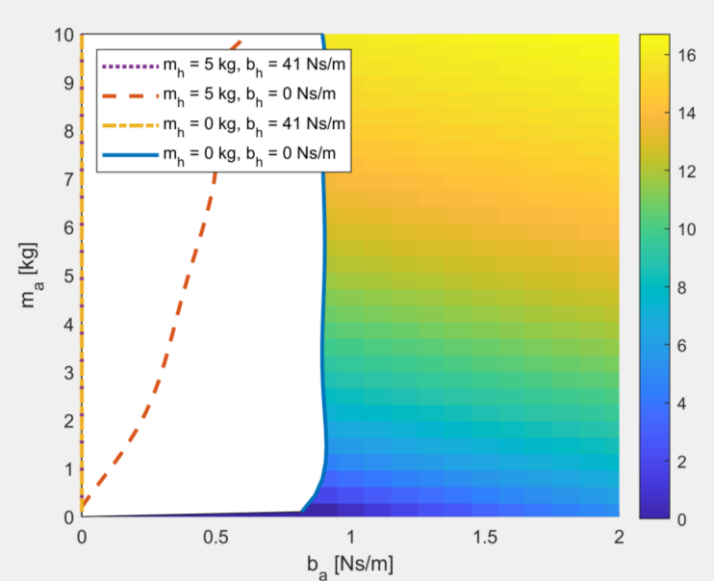

[2] Aydin, Y., Sirintuna, D., & Basdogan, C. (2020). Towards collaborative drilling with a Cobot using admittance controller. *Transactions of the Institute of Measurement and Control*, *43*(8), 1760–1773. https://doi.org/10.1177/0142331220934643

# Mass Spring Damper Simulations: Successful Results

- Observed expected results from our own mass spring damper simulations and analysis of closed loop poles.
- Result was unstable with expected unstable admittance values and stable with expected stable admittance values with simulated damping.

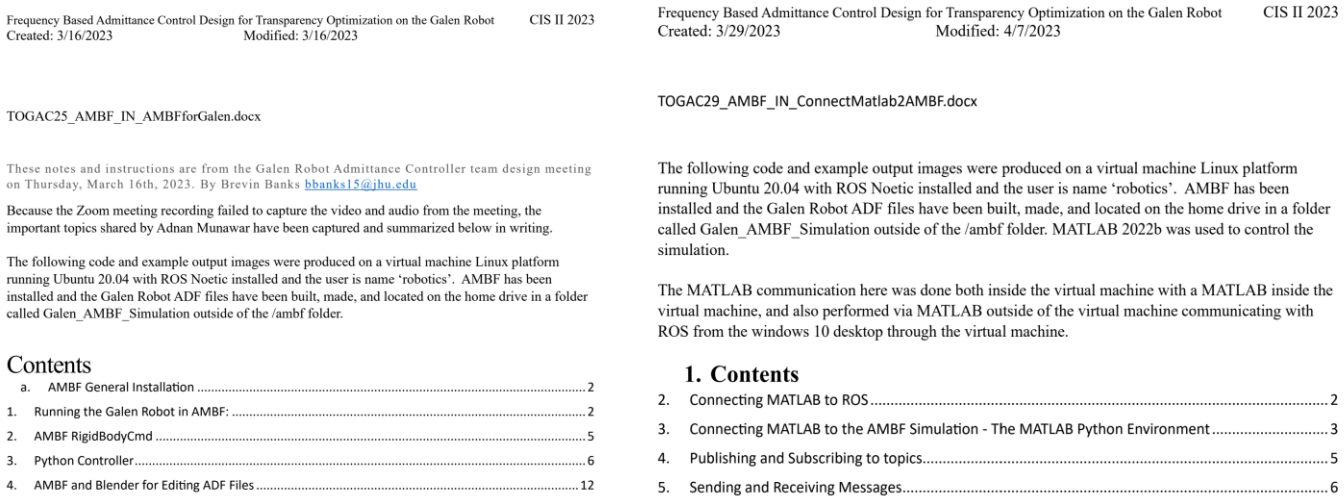



Stability with simulated human and environment impedance




Stability with only simulated human impedance

# Galen robot controller in AMBF through MATLAB



Frequency Based Admittance Control Design for Transparency Optimization on the Galen Robot CIS II 2023
Created: 3/16/2023 Modified: 3/16/2023

TOGAC25_AMBF_IN_AMBFforGalen.docx

These notes and instructions are from the Galen Robot Admittance Controller team design meeting on Thursday, March 16th, 2023. By Brevin Banks bbanks15@jhu.edu

Because the Zoom meeting recording failed to capture the video and audio from the meeting, the important topics shared by Adnan Munawar have been captured and summarized below in writing.

The following code and example output images were produced on a virtual machine Linux platform running Ubuntu 20.04 with ROS Noetic installed and the user is name 'robotics'. AMBF has been installed and the Galen Robot ADF files have been built, made, and located on the home drive in a folder called Galen_AMBF_Simulation outside of the /ambf folder.

Contents


a. AMBF General Installation ..... 2
1. Running the Galen Robot in AMBF: ..... 2
2. AMBF RigidBodyCmd ..... 5
3. Python Controller ..... 6
4. AMBF and Blender for Editing ADF Files ..... 12




Frequency Based Admittance Control Design for Transparency Optimization on the Galen Robot CIS II 2023
Created: 3/29/2023 Modified: 4/7/2023

TOGAC29_AMBF_IN_ConnectMatlab2AMBF.docx

The following code and example output images were produced on a virtual machine Linux platform running Ubuntu 20.04 with ROS Noetic installed and the user is name 'robotics'. AMBF has been installed and the Galen Robot ADF files have been built, made, and located on the home drive in a folder called Galen_AMBF_Simulation outside of the /ambf folder. MATLAB 2022b was used to control the simulation.

The MATLAB communication here was done both inside the virtual machine with a MATLAB inside the virtual machine, and also performed via MATLAB outside of the virtual machine communicating with ROS from the windows 10 desktop through the virtual machine.

1. Contents


2. Connecting MATLAB to ROS ..... 2
3. Connecting MATLAB to the AMBF Simulation - The MATLAB Python Environment ..... 3
4. Publishing and Subscribing to topics ..... 5
5. Sending and Receiving Messages ..... 6

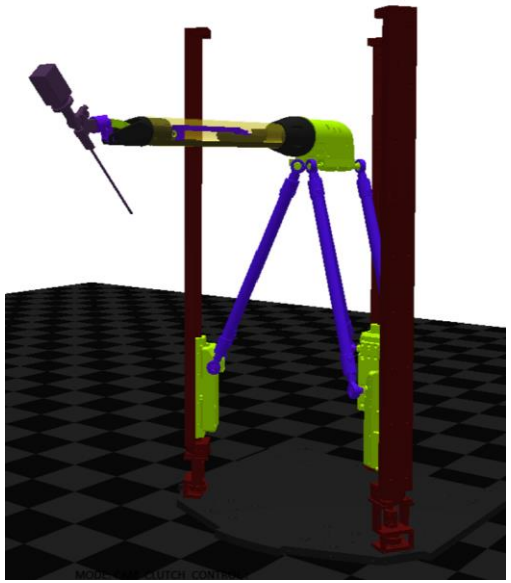

- Creation of a MATLAB interface pipeline for controlling the AMBF environment with ROS Nodes
- Instructions for the installation and use of the interface for the design of the admittance controller
- Scaffolding for simulation's mid-level controller. Discretization of control system at 200Hz using the Tustin transform

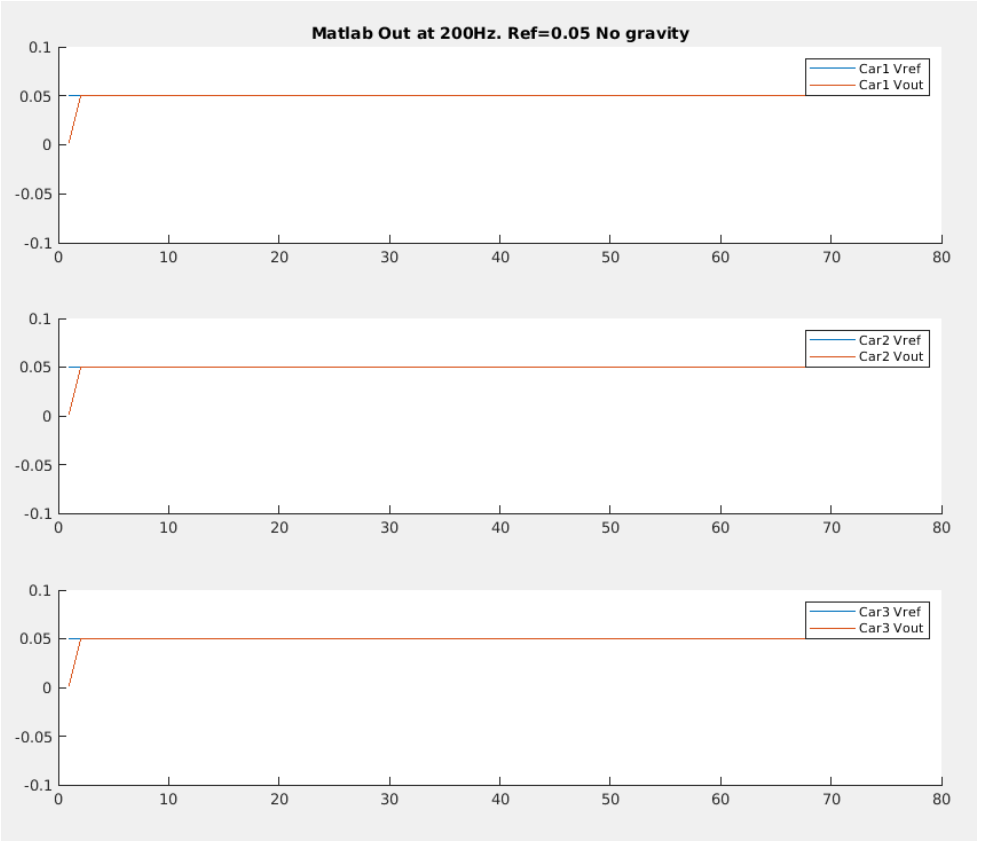
Admittance Discretization

$$\frac{V_{ref}(s)}{F_{net}(s)} = \frac{1}{m_{ad}s + b_{ad}} \rightarrow V_{ref,k} = \frac{-V_{ref,k-1}b_{ad} - {}^{2}/_{T_s}\, m_{ad} + F_{net,k} + F_{net,k-1}}{b_{ad} + {}^{2}/_{T_s}\, m_{ad}}$$

# Galen robot controller in AMBF through MATLAB

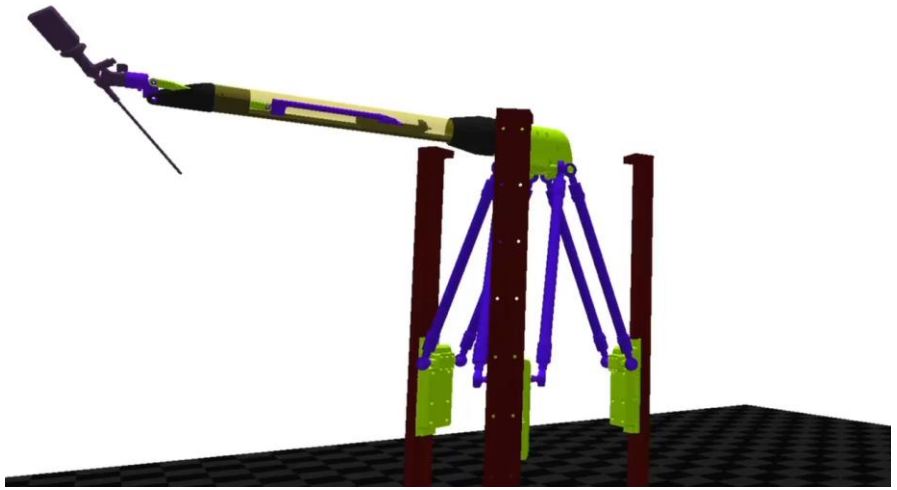
- Joint control at 200Hz with MATLAB to AMBF control interface.
- Move the Galen robot like a mass by giving the 3 carriage joints identical reference velocity
- Turn off gravity as a form of gravity compensation (real identified system will have it within the plant)

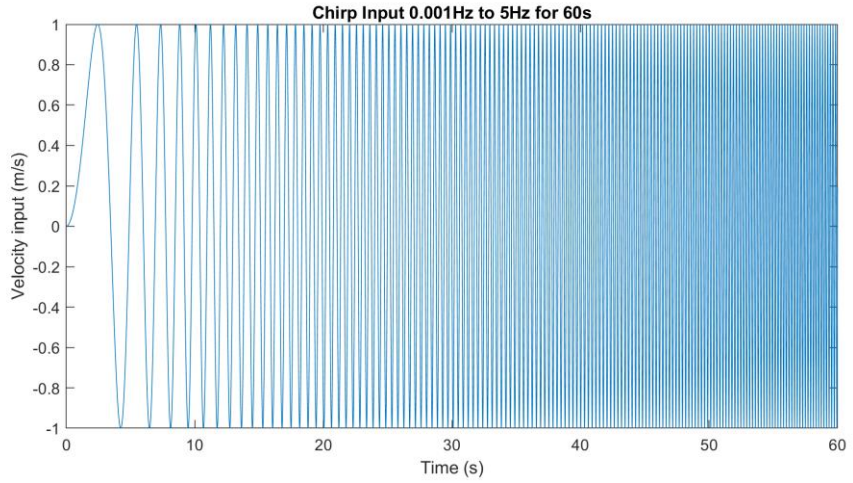




# Simulated System Identification

- Identify P(s) – the robot dynamics. Assume linear even though it's nonlinear. Okay for small steady movements. Should have transfer function similar to mass spring damper in form.
- For cartesian velocity control we required the simulated Galen Jacobian. Derived forward kinematics and Jacobian for the simulated robot.
- Apply input signal. Chirp input in our case. Measure output. MATLAB system Identification tools tf and ssest help find at least a 2nd order estimate for P(s)

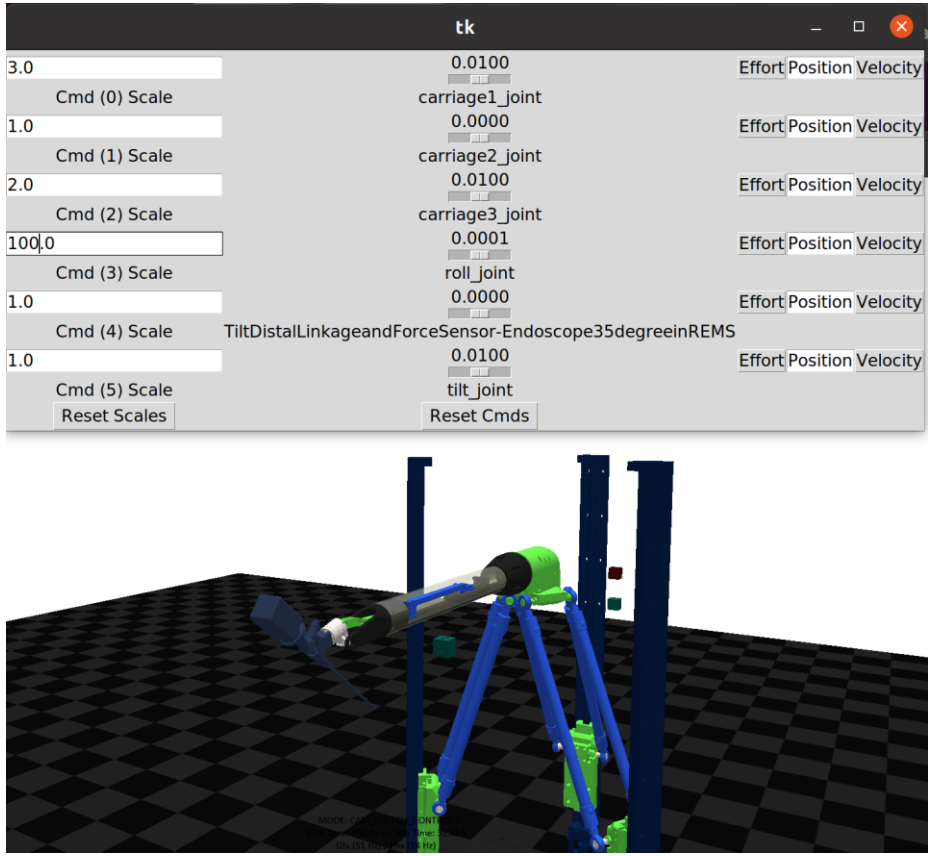




# Simulated System Identification: Results

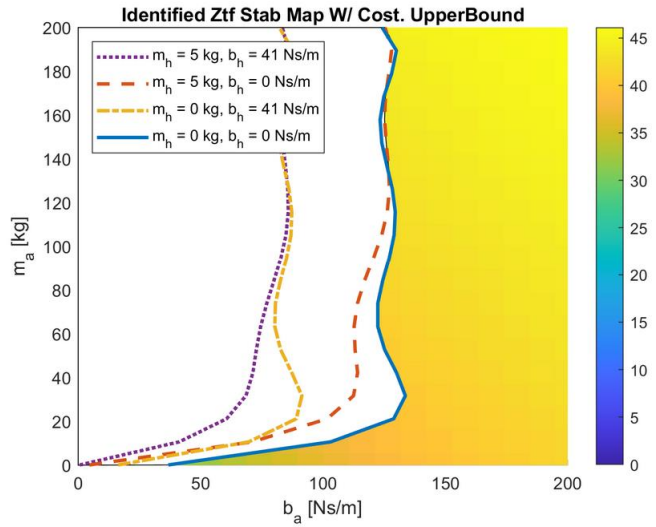
- Verified Jacobian and Forward kinematics of the robot with cartesian control.
- Resultant identified transfer functions

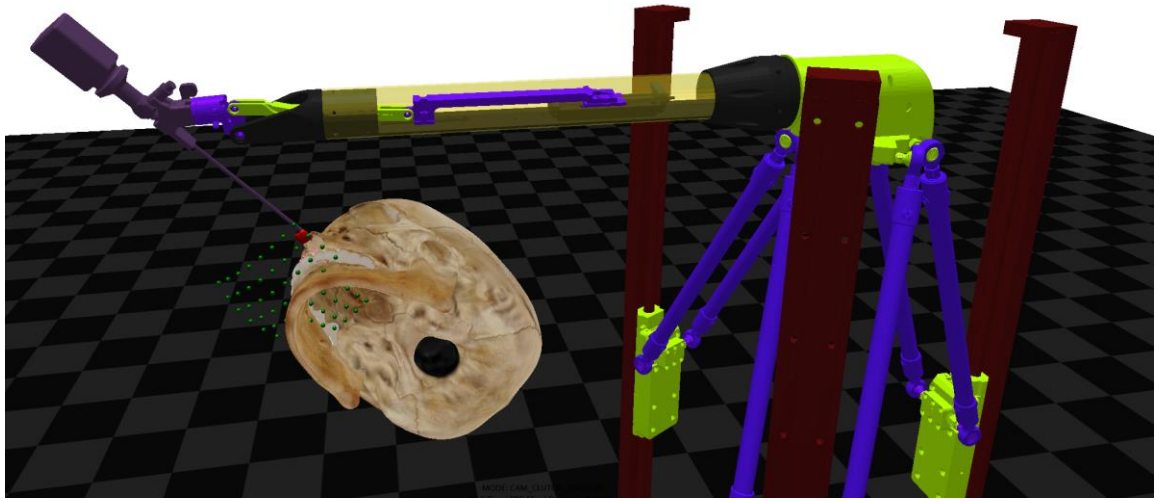
| Velocity Component | Transfer Function | Quality of Match |
|---|---|---|
| Vx | 132.8/(s + 145.8) | 77.93% |
| Vy | 131.8/(s + 132.4) | 92.15% |
| Vz | 1.973e06/(s^2 + 1.558e04*s + 1.975e06) | 92.58% |
| Wx | 2.542e05/(s^2 + 153.1*s + 2.561e05) | 89.39% |
| Wy | 1.587e04/(s^2 + 230.7*s + 1.584e04) | 91.03% |



# Application of Admittance Controller in AMBF

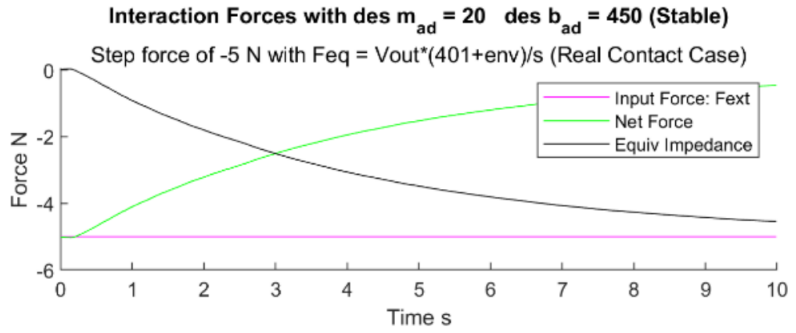
- Test the stability of identified transfer functions. Find acceptable and unacceptable m_ad and b_ad values
- Test in actual contact with object



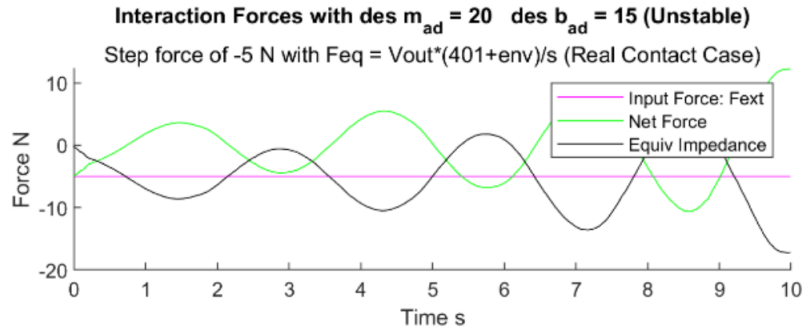



# Application of Admittance Controller in AMBF

- When in contact with the skull the stable m_ad and b_ad admittance control remains stable. The unstable m_ad and b_ad goes unstable as expected




Contact Case (mh=0,bh=0,kh=401,with sim ke). Data captured at 200 Hz and Stable

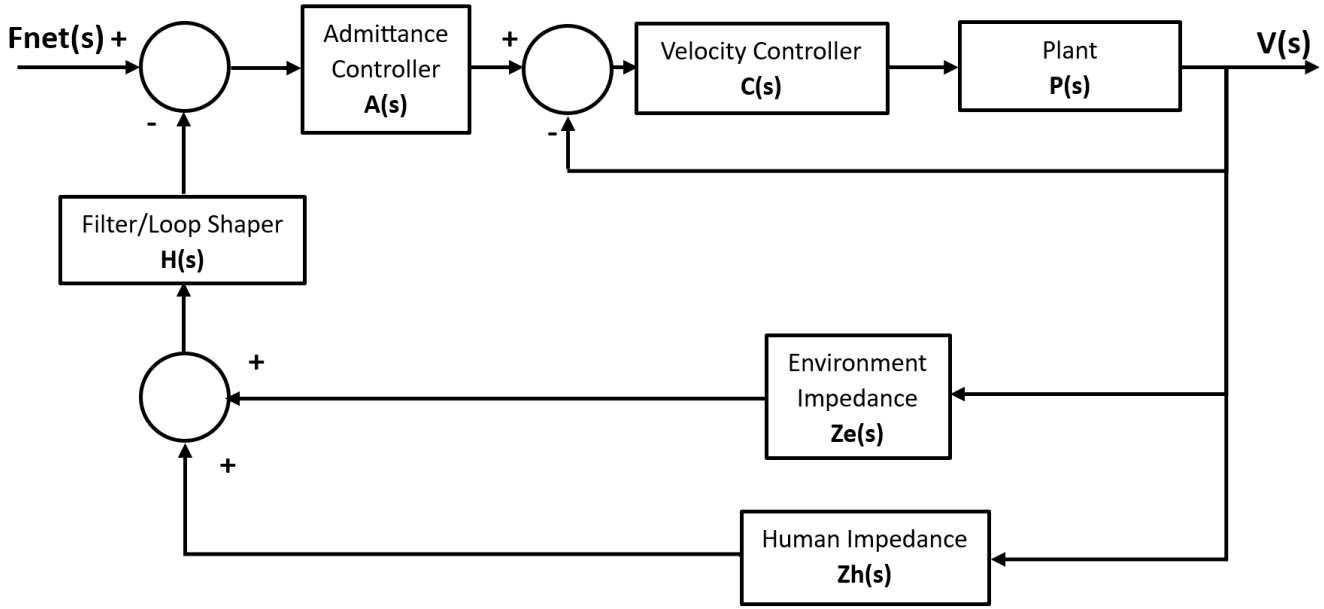


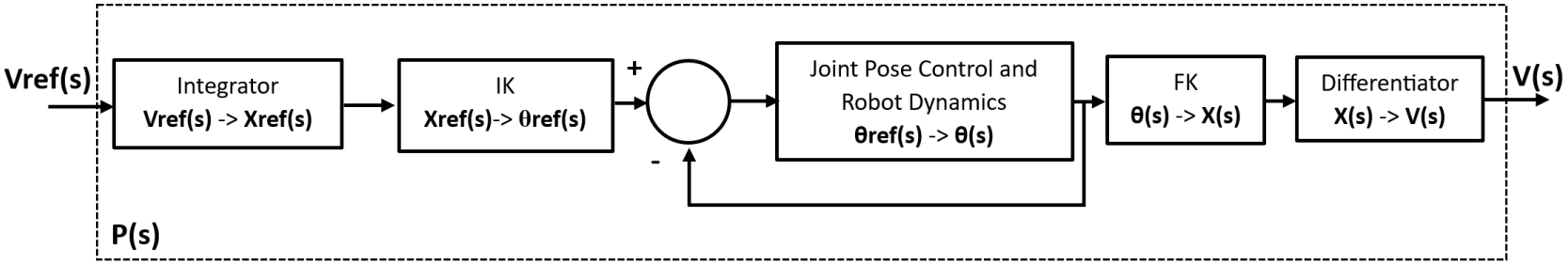

Contact Case (mh=0,bh=0,kh=401,with sim ke). Data captured at 200 Hz and Unstable

# Setback discussion

- Feasibility of controller design took longer than expected to validate with previous literature
- System identification was not entirely conceived within the scope of this project and the deliverable for that has become more critical.
- Mentors decided to move the user study for now to focus on the more pressing design of the controller and implementation virtual fixtures.

# Justification for Deliverables Adjustment




- Implementation of velocity control in cartesian space
- Simulated model differs largely from real hardware
- System identification simplifies P(s)

# Updated Deliverables

**Minimum: Due 4/18/2023**

- A stable frequency domain admittance controller in MATLAB code for the Galen surgical robot in the AMBF simulation environment Completed
- A simulated control system package with optimized transparency containing code files that can be used in AMBF and MATLAB and is transferable to hardware Completed

**Expected: Due 4/25/2023**

- An applied control system package to the low-level Galen controller that is stable and optimized for transparency including virtual fixtures In progress
- A validated objective improvement in transparency according to specified metrics, with identified system dynamics In progress

**Maximum: Due 5/5/2023**

- Implemented Virtual Fixtures that constrain the robot hardware within desired simulated bounds. Waiting

**Extended Maximum: TBD**

- During the summer a completed user study to investigate subjective transparency preference with different controllers on the Galen robot Waiting

# Project Dependencies

| Dependency | Need | Contingency Plan | Planned Deadline | Hard Deadline | Status |
|---|---|---|---|---|---|
| Access to Computer | Need a computer with a Linux platform | Use a lab computer | 8-Feb | 13-Feb | Completed |
| Access to Galen AMBF Model | File access and editing permissions | Create a basic 3D model and crude dynamics | 14-Feb | 20-Feb | Awaiting Files |
| Software Installation MATLAB SIMULINK | License | Use Lab Computer with preinstalled software | 8-Feb | 13-Feb | Completed |
| Software Blender and AMBF Addon | Installation Instructions | Use Lab Computer with preinstalled software | 8-Feb | 13-Feb | Completed |
| Galen Robot and Controller Access | Anton and Adnan complete controller pipeline for Galen task space and joint space control | Go without Galen hardware implementation. Implement on similar robot or move on without implementation | 15-Mar | 15-Apr | Completed |
| IRB for user study | IRB Approval | Go without the User Study | (Submission 20-Feb) 3-Apr | (Submission 24-Feb) 17-Apr | ON HOLD FOR SUMMER |

# Previous Project Timeline

## Transparency Optimization of the Galen Surgical System With Frequency Domain Admittance Controller Design

LSCR CIS 2

Brevin Banks

Project Start: Mon, 2/13/2023

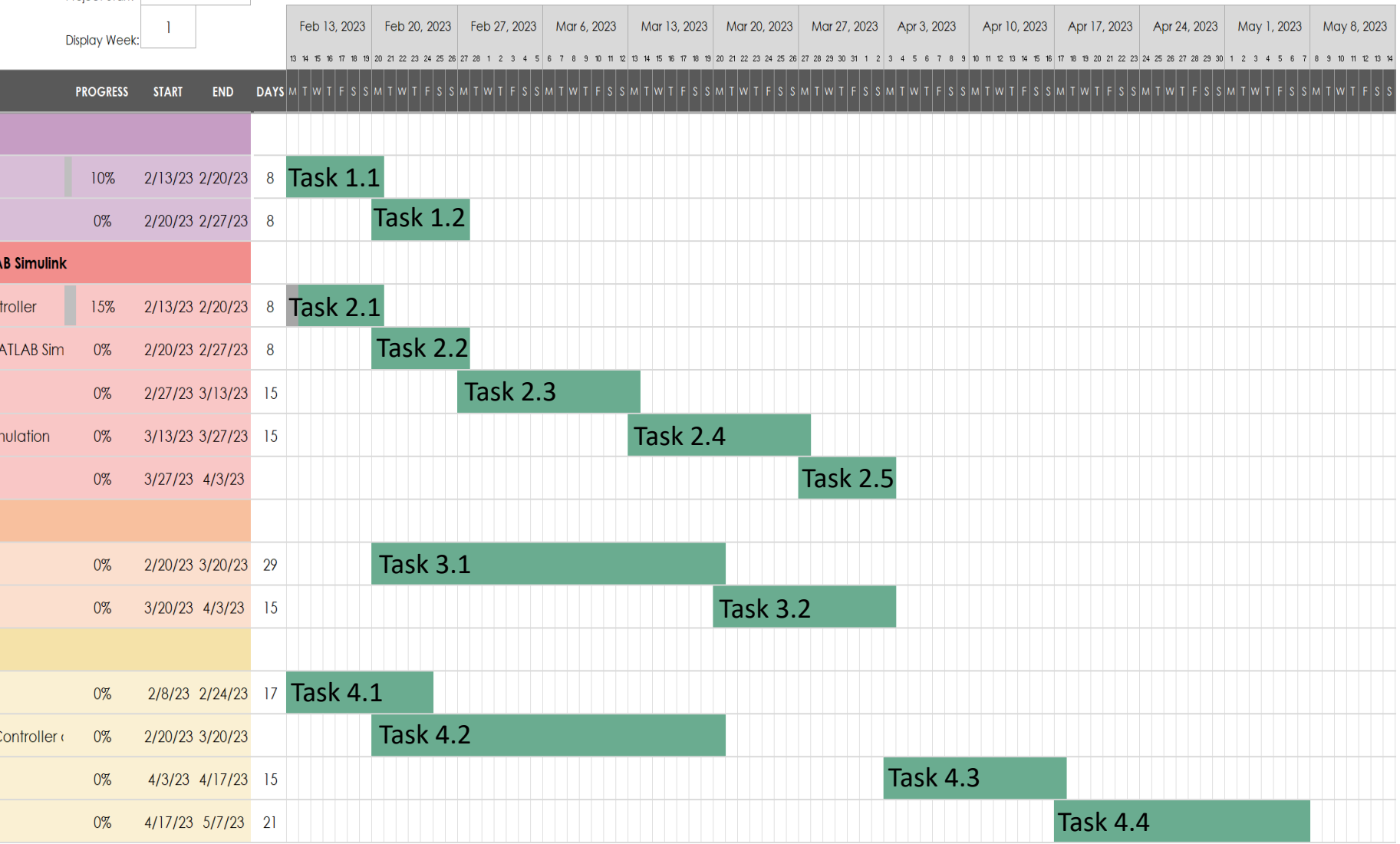
Display Week: 1

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Engineering Research Center for Computer Integrated Surgical Systems and Technology

| TASK | PROGRESS | START | END | DAYS |
|---|---|---|---|---|
| **Simulated Environment Setup and Correction** | | | | |
| Connect and Familiarize with AMBF and MATLAB Environment for Simulation | 10% | 2/13/23 | 2/20/23 | 8 |
| Update Simulated Galen Robot Dynamics | 0% | 2/20/23 | 2/27/23 | 8 |
| **Frequency Admittance Controller and Transparency Optimization in AMBF & MATLAB Simulink** | | | | |
| Brainstorm Methods for Implementing Simple Linear Frequency Admittance Controller | 15% | 2/13/23 | 2/20/23 | 8 |
| Implement a Linear Controller Modeling the Galen as Mass Spring Damper in MATLAB Sim | 0% | 2/20/23 | 2/27/23 | 8 |
| Assess and Optimize Transparency and Stability of Controller in MATLAB | 0% | 2/27/23 | 3/13/23 | 15 |
| Convert the Controller Plant to Robot dynamics, Update, and apply to AMBF Simulation | 0% | 3/13/23 | 3/27/23 | 15 |
| Add Virtual Fixture to the Controller in AMBF | 0% | 3/27/23 | 4/3/23 | |
| **Low Level Galen Controller and Validating Transparency Improvement** | | | | |
| Apply Simulated Controller to Real Galen | 0% | 2/20/23 | 3/20/23 | 29 |
| Testing of the Controller | 0% | 3/20/23 | 4/3/23 | 15 |
| **User Study For Subjective Transparency Preferences With Various Controllers** | | | | |
| IRB Proposal Submission | 0% | 2/8/23 | 2/24/23 | 17 |
| Design User Study for Testing New Galen Controller with Respect to the Current Controller | 0% | 2/20/23 | 3/20/23 | |
| Recruit Users and Perform Testing | 0% | 4/3/23 | 4/17/23 | 15 |
| Analyze Data and Conduct Further Research/Write Paper | 0% | 4/17/23 | 5/7/23 | 21 |



# Previous Project Timeline

## Transparency Optimization of the Galen Surgical System With Frequency Domain Admittance Controller Design

LSCR CIS 2
Brevin Banks

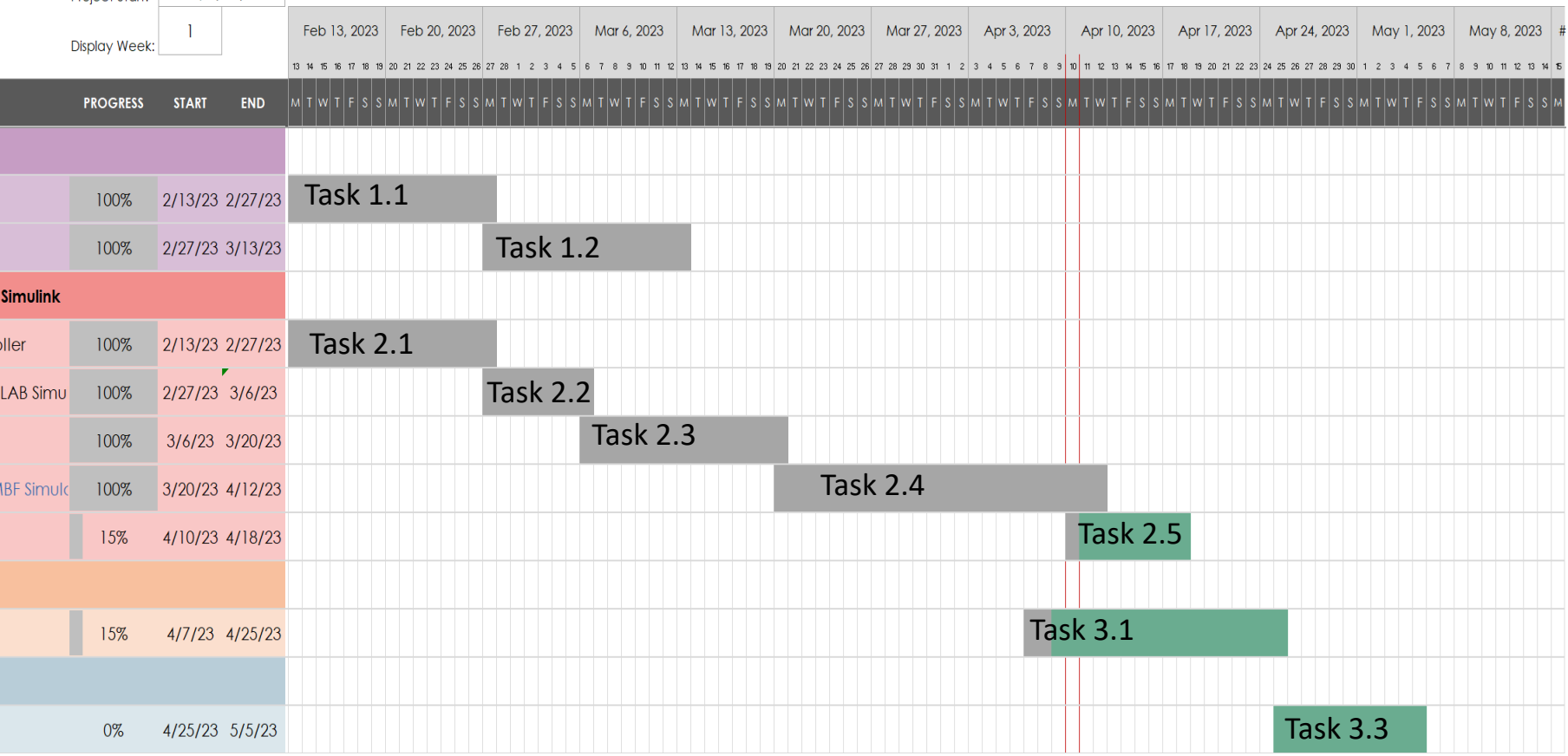
TOGAC7_D_GalenTransparencyControlGanttChart.xlsx

Project Start: Mon, 2/13/2023
Display Week: 1

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Engineering Research Center for Computer Integrated Surgical Systems and Technology

| TASK | PROGRESS | START | END |
|---|---|---|---|
| **Simulated Environment Setup and Correction** | | | |
| Connect and Familiarize with AMBF and MATLAB Environment for Simulation | 100% | 2/13/23 | 2/27/23 |
| Update Simulated Galen Robot Dynamics | 100% | 2/27/23 | 3/13/23 |
| **Frequency Admittance Controller and Transparency Optimization in AMBF & MATLAB Simulink** | | | |
| Brainstorm Methods for Implementing Simple Linear Frequency Admittance Controller | 100% | 2/13/23 | 2/27/23 |
| Implement a Linear Controller Modeling the Galen as Mass Spring Damper in MATLAB Simu | 100% | 2/27/23 | 3/6/23 |
| Assess and Optimize Transparency and Stability of Controller in MATLAB | 100% | 3/6/23 | 3/20/23 |
| Identify Convert the Controller Plant to Robot dynamics, Update, and apply to AMBF Simul | 100% | 3/20/23 | 4/12/23 |
| Add Virtual Fixture to the Controller in AMBF | 15% | 4/10/23 | 4/18/23 |
| **Low Level Galen Controller and Validating Transparency Improvement** | | | |
| Apply Simulated Controller to Real Galen | 15% | 4/7/23 | 4/25/23 |
| **User Study For Subjective Transparency Preferences With Various Controllers** | | | |
| Implement Virtual Fixtures on Real Galen Hardware | 0% | 4/25/23 | 5/5/23 |



# Updated Project Milestones (Updates in blue)

**Group 1: (Tasks 1.1 done in Parallel with tasks 2.1)**

Task 1.1) Connect and Familiarize with AMBF and MATLAB Environment for Simulation
Planned Date: 2/13 Expected Date: 2/27 COMPLETED

Task 1.2) Update Simulated Galen Robot Dynamics
Planned Date: 2/27 Expected Date: 3/13 COMPLETED

**Group 2:**

Task 2.1) Brainstorm Methods for Implementing Simple Admittance Controller and Choose Transparency Metrics
Planned Date: 2/13 Expected Date: 2/27 COMPLETED

Task 2.2) Implement a Linear Controller Modeling the Galen as Mass Spring Damper in MATLAB Simulink Simulation
Planned Date: 2/27 Expected Date: 3/6 COMPLETED

Task 2.3) Assess and Optimize Transparency and Stability of Controller in MATLAB
Planned Date: 3/6 Expected Date: 3/20

Task 2.4) Convert the Controller Plant to Robot dynamics, Update, and apply to AMBF Simulation
Planned Date: 3/20 Expected Date: 4/12 COMPLETED

Task 2.5) Add Virtual Fixture to the Controller in AMBF
Planned Date: 4/10 Expected Date: 4/18 In progress

**Group 3: (Tasks 3.1 on going during all of tasks in group 2)**

Task 3.1) Apply Simulated Controller to Real Galen Hardware.
Planned Date: 4/7 Expected Date: 4/25 In progress.

Task 3.3) Implement Virtual Fixtures on Real Galen Hardware
Planned Date: 4/25 Expected Date: 5/5 Waiting

# Plan to Deal With Setbacks

Working with Mohammad Wednesday 10Am to perform system identification

Unlikely, but in the case that system identification proves problematic, we will stick to applying the controller as if it is a mass in one DOF (most likely Z)

The controller development on the actual Galen system will be performed with the high/mid level python crtk servo cv commands

Development of virtual fixture prototypes have already started. Use spring approximation instead of finite element method.

# Project Management

Brevin – Controller Design, Implementation, Stability and Transparency Analysis.

Weekly meetings with mentors Mondays at 1:30 PM

- See wiki for Document Control Scheme
- MATLAB functions on private GitHub as instructed by mentor. Transferring to Lab repo
- No Galen code is on that repo.
- All Galen code stays within the mock OR and the Bitbucket branch. No local versions

# References


- Democratizing Robotic Surgery and Microsurgery. Galen Robotics. (2022, November 15). Retrieved February 13, 2023, from https://www.galenrobotics.com/
- Aydin, Y., Sirintuna, D., & Basdogan, C. (2020). Towards collaborative drilling with a Cobot using admittance controller. *Transactions of the Institute of Measurement and Control*, *43*(8), 1760–1773. https://doi.org/10.1177/0142331220934643
- Keemink AQ, van der Kooij H, Stienen AH. Admittance control for physical human–robot interaction. The International Journal of Robotics Research. 2018;37(11):1421-1444. doi:10.1177/0278364918768950
- Williams, R. L. (2016). The Delta Parallel Robot: Kinematics Solutions. Mechanical Engineering: Ohio University, 1–46.