TOGAC34_AMBF_R_LumpedSystemIdentification.docx

Modeling the Galen Robot Carriage Joints as a single lumped mass spring damper

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Preface

This document is to record the history for testing runtime delays and frequency testing, system identification, and initial admittance control testing for the Galen Robot. These items were all done under the assumption that the AMBF ADF model for the galen robot can be used as a single mass spring damper with a lumped system mass. This is done by ensuring that the input and output of the 3 translational joints that form the carriage joints of the delta platform are identical in their response.

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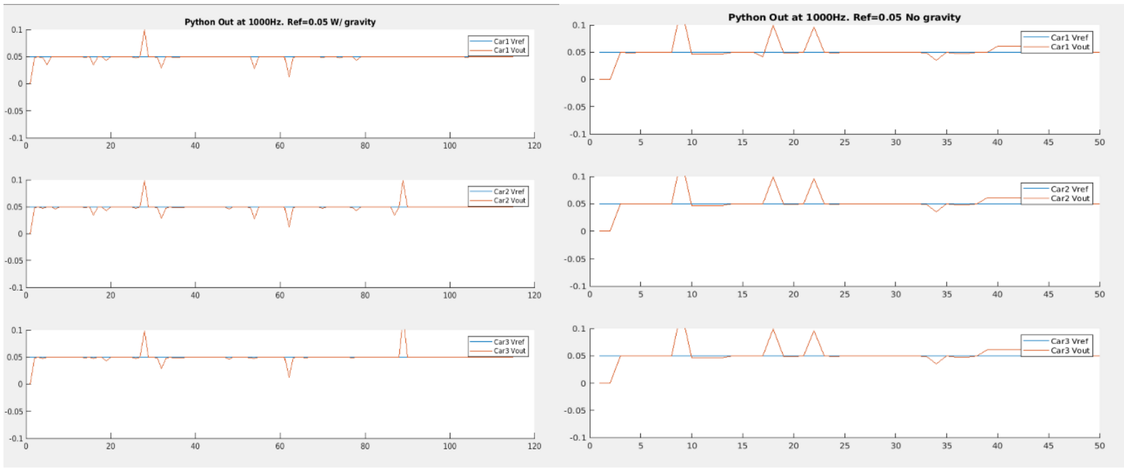
VM Frequency Test. MATLAB VS Python Controller

Initially test were performed with matlab and AMBF running on the same Virtual Linux machine.

These figures below represent the performance of the AMBF simulation on the galen robot from these tests. A step velocity is commanded via a ROS publisher, and the output velocity is messured from a ROS subscriber.

The robot performed differently depending on the AMBF initialization frequency and whether gravity was on or not. Any large spikes or deviations from the reference indicate where the sampling time was delayed or slowed. ROS was either waiting for messages or still executing messages before the next one came. The output show is the output of the three carriage joints of the Galen Robot from the delta platform.


Python Out at 1000Hz. Ref=0.05 W/ gravity
Python Out at 1000Hz. Ref=0.05 No gravity
Car1 Vref
Car1 Vout
Car2 Vref
Car2 Vout
Car3 Vref
Car3 Vout
0.1
0.05
0
-0.05
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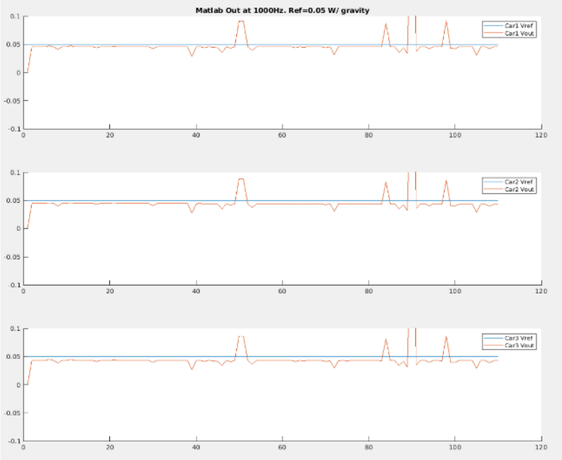
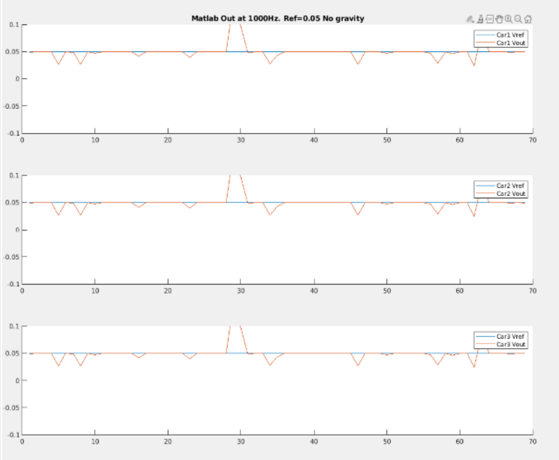
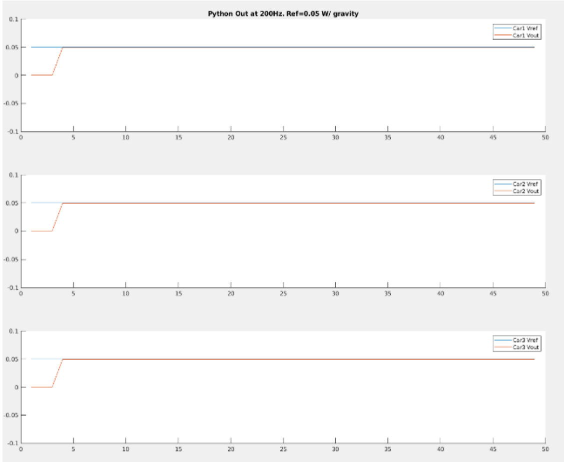
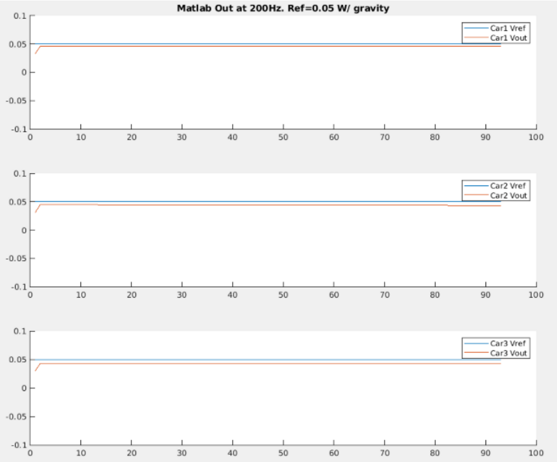
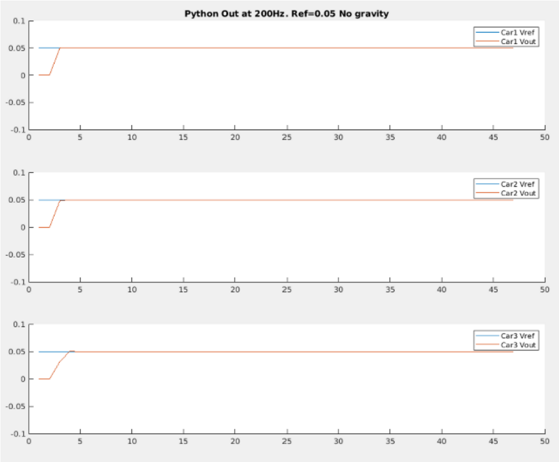
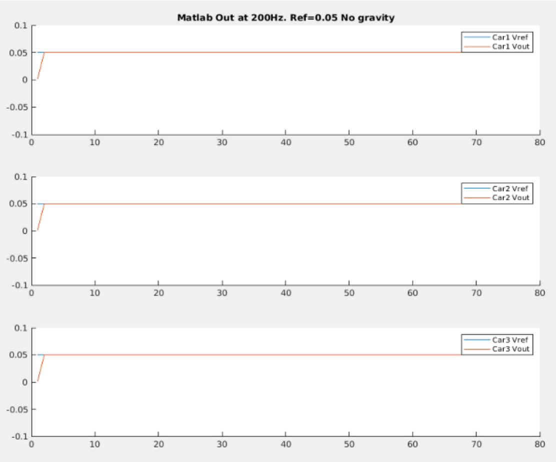








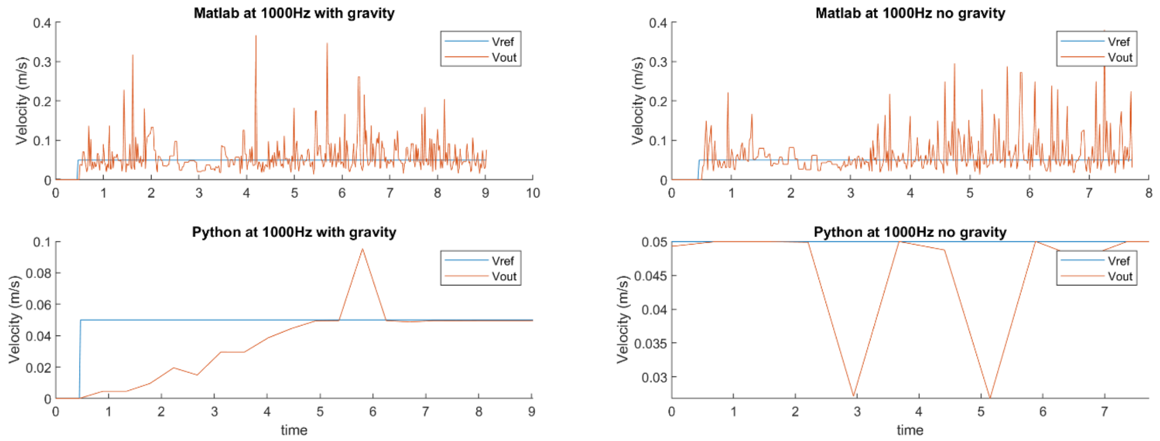


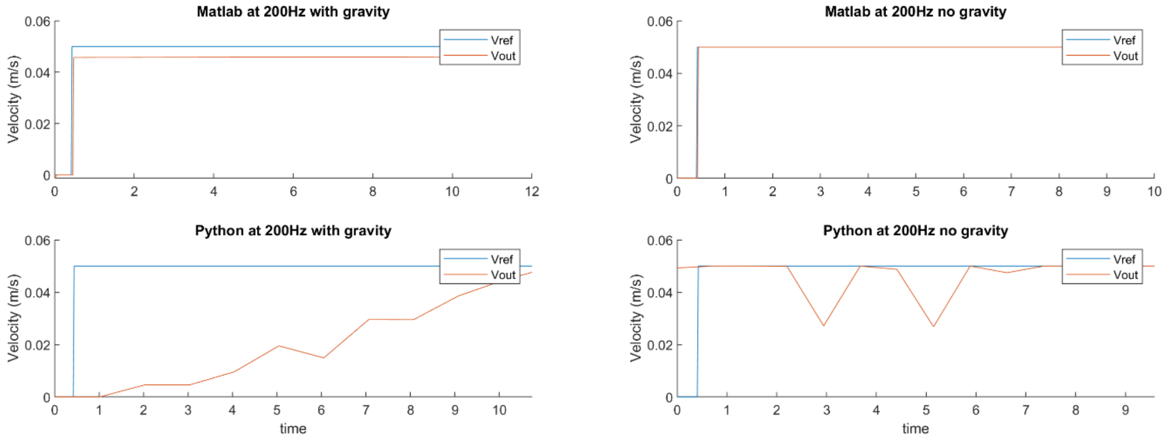


It was determined that matlab can still be used if the frequency is at least 200Hz. Steady state error will be present in the case of gravity due to the AMBF low level controller not supporting gravity compensation directly.

Outside of VM MATLAB

Because of the significant latency issues from MATLAB communication with ROS, I choose to use MATLAB outside of the virtual linux machine on the Windows 10 Host machine. This required ROS networking and a direct connection via the linux VM’s IP address and ROS master name. The connection allowed for much faster communication. But communication at 1000 Hz still had significant amounts of noise present, so 200Hz remains the chosen sampling frequency. The results are compared to the previous python outputs inside the VM from the previous section.



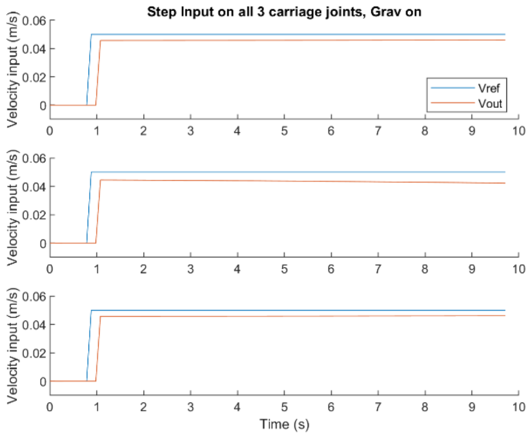


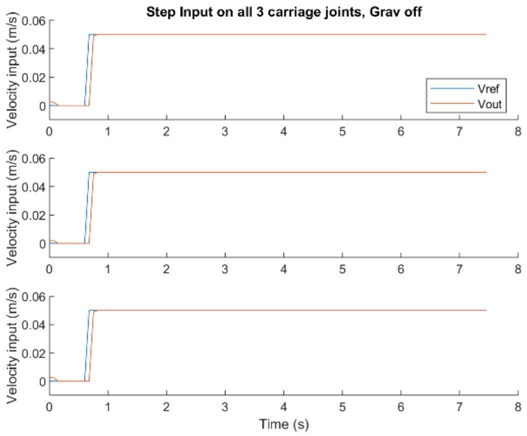
System Identification Setup: Step vs Chirp

With a working controller in MATLAB, the system was identified as a linear system according to step and chirp inputs. The identification methods used were MATLAB’s iddata and tfests functions with 2nd order initial guesses, as well as another iterative solution using MATLABS ssest function to find the best matching system order for the output transfer function. These tools are part of the MATLAB system Identification toolbox.

2 measurement sets of data were collected to see how they affected the output transfer functions. One set with gravity on and the other with gravity off. Ultimately the gravity off functions would be used, but it is interesting to note the gravity only mildly affected the quality of the output transfer function.

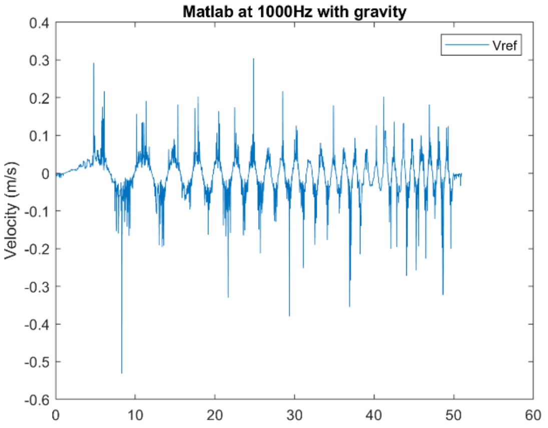
The below figures are the results of a step input with gravity on and off for the carriage joints.

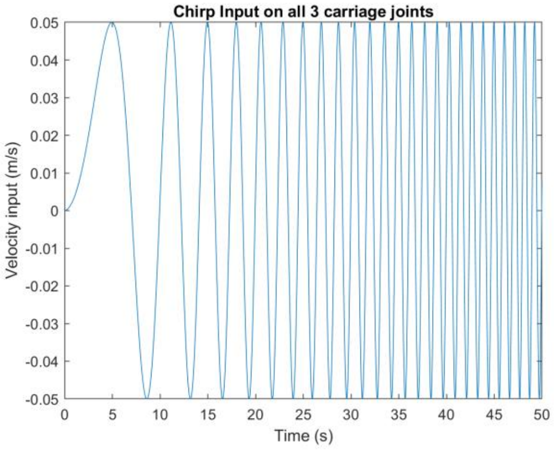




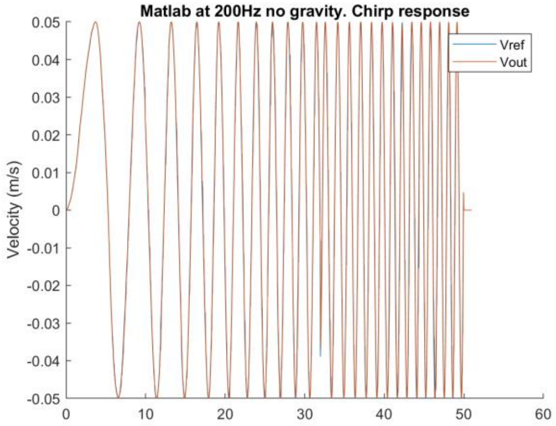
Similarly a chirp input was applied to the galen robot from 1Hz to 100Hz (slightly smaller than the reasonable range of human motion (10^-2 to 10^2).

On the left is an example of why matlab must be run below 1000 Hz. Although the legend says it is the Vref, it is actually the robot output velocity, and there is too much noise. On the right an example of a 50 second output of chirp data from 1Hz to 100Hz that was used as a trajectory reference velocity for system identification.





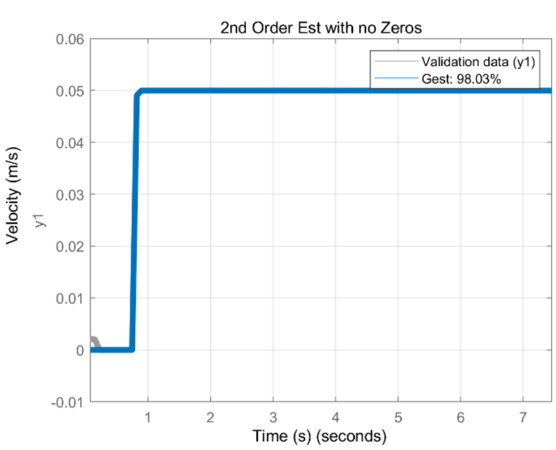
The output response of the robot for a single carriage joint (all three were ran simultaneously and the output was assumed to be identitical) at 200Hz on this trajectory is shown below.

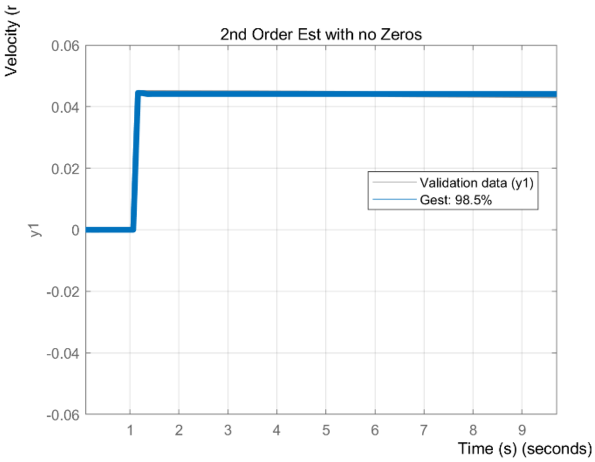


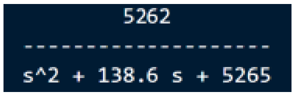
System Identification Results

The left shows the results of the tfest 2nd order estimate output TF for a step response without gravity. The right shows the results of the tfest 2nd order estimate output TF for a step response with gravity. The respective output TF is shown below the figure. Although the % match is really close for the case with gravity, we aren't trying to control for a present steady state error so the system on the left will be used.

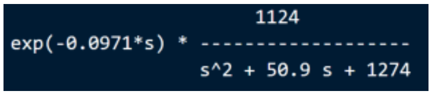
We are assuming that turning off gravity for the system during simulation will provide a sort of pseudo gravity compensation for the robot for the time being.





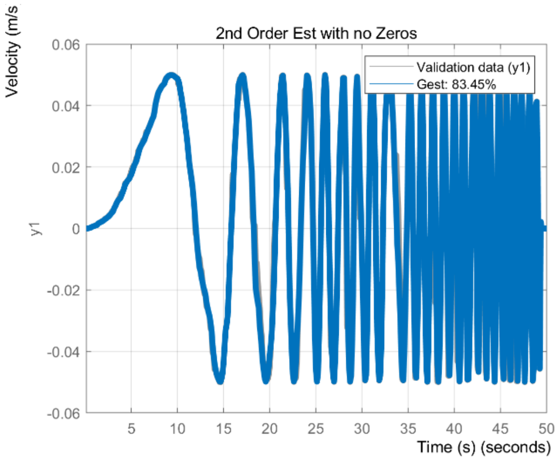


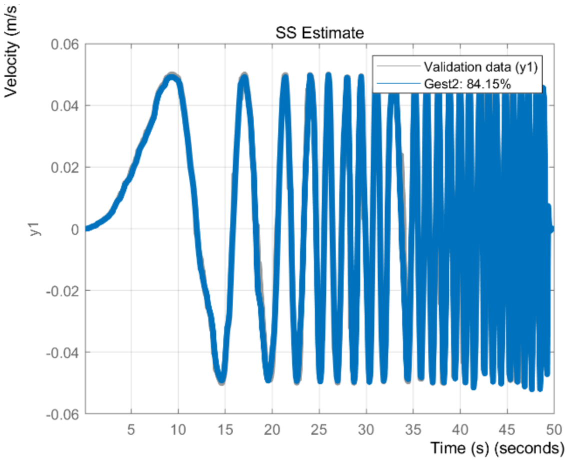
```
         5262
--------------------
s^2 + 138.6 s + 5265
```

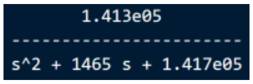


```
                          1124
exp(-0.0971*s) * ------------------
                 s^2 + 50.9 s + 1274
```

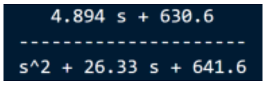
The system was identified using the chirp data. This was done with the gravity off. Both Tfest and ssest were used to find closely matching TF’s. On the left is the response using Tfest with a 2nd order estimation and the right is an ssest 2nd order estimation that was the best of options 1st order through 10nth order including zero cancelations.







```
       1.413e05
----------------------
s^2 + 1465 s + 1.417e05
```



```
   4.894 s + 630.6
---------------------
s^2 + 26.33 s + 641.6
```

Interestingly, even with the chirp estimated transfer function, when the step response from above without gravity’s transfer function was given the same chirp trajectory, the output of the Galen robot output velocity matched the true chirp trajectory better than the chirp estimated transfer function.

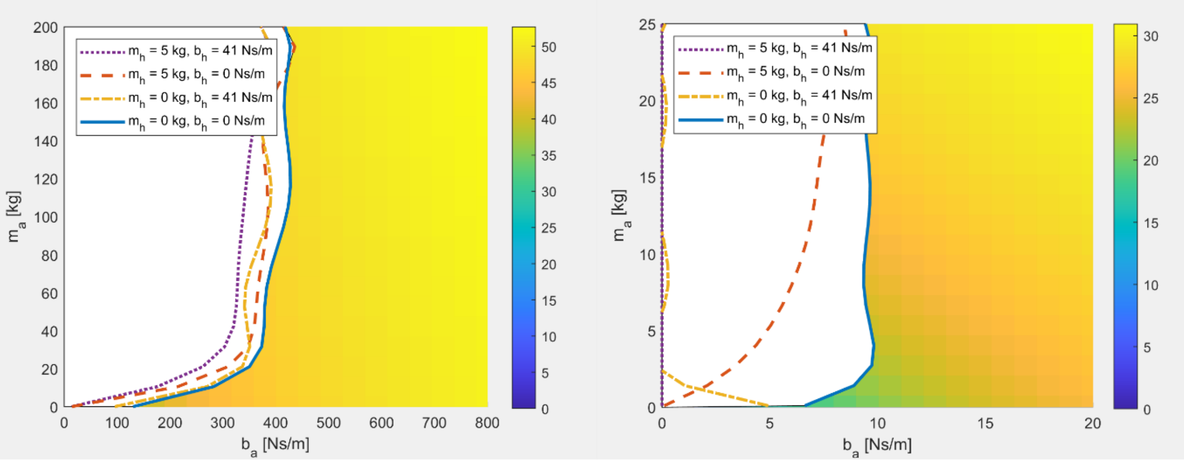
Because of this the no gravity step response system, $TF = \frac{5262}{S^2+138.6S+5265}$, was chosen as the system identification TF result to be used in testing of the simulation model.

Stability Analysis of the Identified System

The closed loop poles of the transfer function were observed and a stability map for different desired admittance mass and damping values was made.

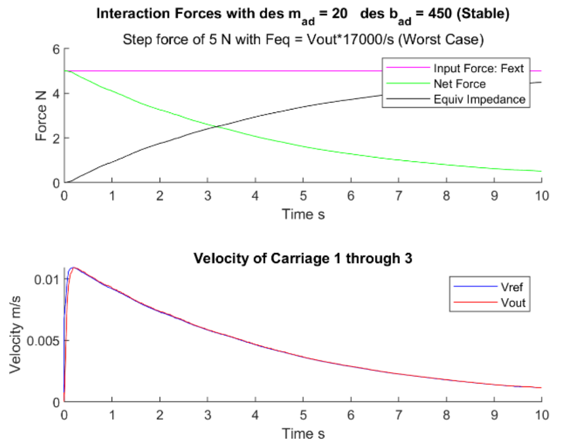
The figures below descirbe regions where the robot is garunteed to perform with a stable response given a human force is interacting with the robot moving it up or down. The human force also imposes an impedance on the robot that will slow it and change the system dynamics. These human factors are modeled by the upper and lower extreme bounds of the human interaction. Contact with the environment is also taken into account, such that any contact is assumed to take on a maximum stiffness value that impedes that robot similar to the human. These bounded values are as follows. Human and environment impedance: Upper bound, mass mh = 5 damping bh = 41 stiffness kh = 401 Environment ke = 16599; Lower bound, mass mh = 0 damping bh = 0 stiffness kh = 401 Environment ke = 0;

The output for the case with high envrionmnet impedance (16599) is on the left. The case on the right has no environment impedance. Thus, Any value in the shaded yellow/green region in the left figure will result in addmittance controller values acceptable for all human environment interactions. The more blue/green the acceptable values are, the more transparent the controller will feel.

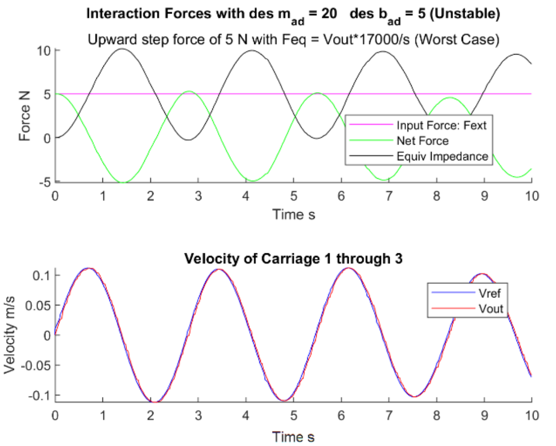


Simulated Admittance Application

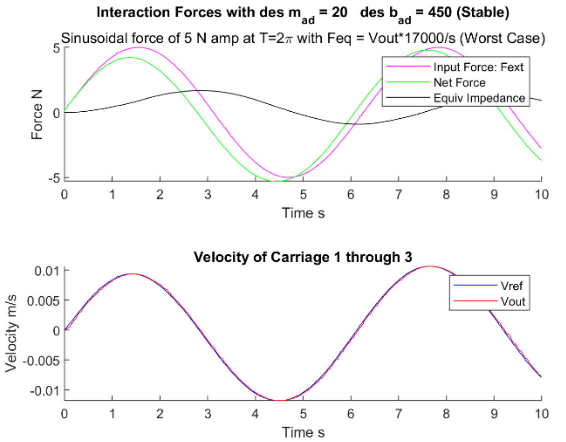
An admittance controller was applied to the identified TF with different admittance mass m_ad and damping b_ad values that were in the stable region and unstable region. The expected output of the control follows suit to the stability map. Stable values result in stable outputs. Unstable values result in unstable outputs. Different input cases were used. First a step input of constant 5 newtons was applied. Then a sine force of amplitude 5 was applied. This simulation was done assuming that both human and environmental impedance were present at their worst-case values.



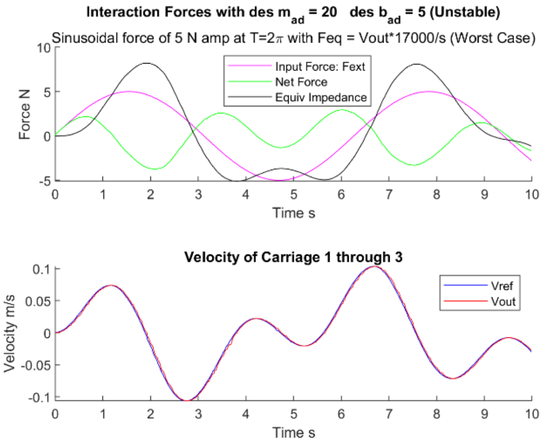
Worst Case (mh=0,bh=0,kh=401,with full ke. Data captured at 200 Hz and Stable



Worst Case (mh=0,bh=0,kh=401,with full ke. Data captured at 200 Hz and Unstable



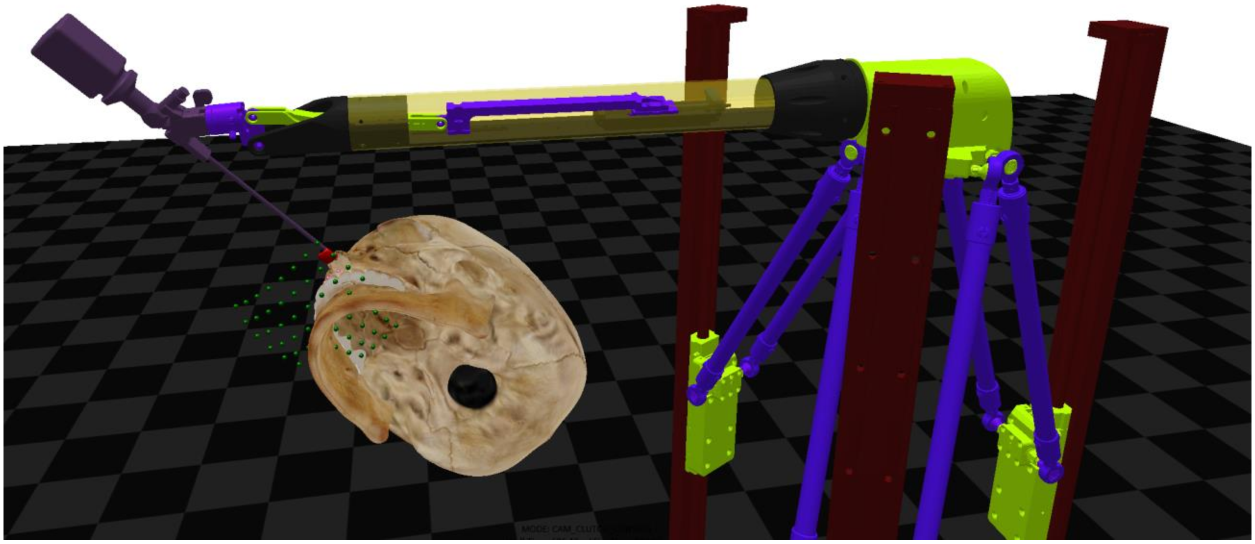
Worst Case (mh=0,bh=0,kh=401,with full ke. Data captured at 200 Hz and Stable



Worst Case (mh=0,bh=0,kh=401,with full ke. Data captured at 200 Hz and Unstable

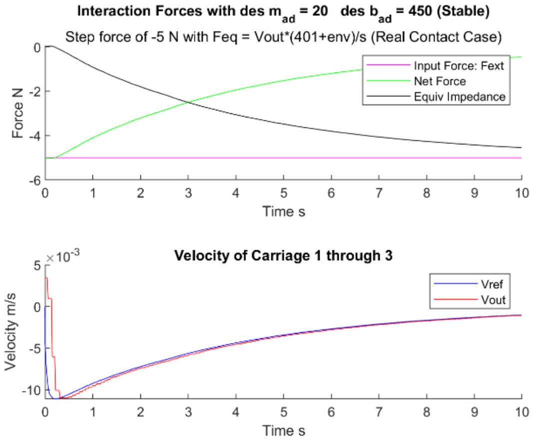
Simulated Admittance Application with Contact

The admittance controller from above was applied to the AMBF Galen Robot simulation. The environmental impedance was removed and assumed to be present during any true environmental contact within the simulation. In this case the contact would be represented by collision of the robot with the skull. The skull is assumed to be fixed and have a fixed contact stiffness.

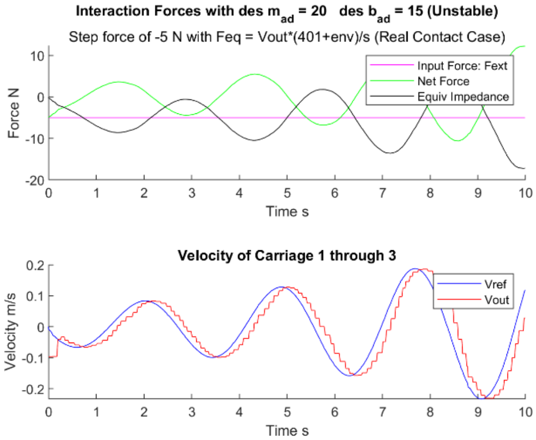


To use the controller in the simulation environment, the transfer function of the admittance controller and human impedance were discretized with a sample time of 200Hz. The discretization was done using a linear tustin transform and previous force and velocity time steps were required to be recorded during the control loop. The initial force and velocity were set to 0.

In this scenario the robot was placed above the skull as shown in the figure above. The tool of the robot was placed such that it would be garunteed to contact the skull during a descent of the robot. It was assumed that the human would input a small 5 Netwon force downward on the robot and try to move the tool into the skull. The velocity output of the interaction is shown by the figures below.



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

In the case of the unstable admittance values, the robot would go unstable during contact. This did not always occur, but the unpredictability of the robot at these admittance values reflects the instability of the design. It is wise to choose values within the known stable region to get a stable response as shown on the left. Also note that during contacts, the simulation could slow due to collision calculation hampering the performance of the control loop. The frequency would slow and cause delay in the control that lead to further instability. This instability was not a result of the admittance controller or impedance, but a limitation of slower computer hardware. With a different machine for testing it is anticipated that the results would be clearer and more conclusive, but it is still expected that the unstable admittance values would lead to an unstable response during contact.

Current Issues as of 4/1/2023

The simulated controller has performed well in the applications listed above throughout this report. There have been other activities within the project and controller development process that have led to a few hiccups. Currently we are experiencing issues with the following making it difficult to gain confidence in the application of the control scheme.

1. A Matlab Simulink model was made, but it could not connect to ROS. Set aside as less important for the time being.

2. Computer runs well until collsions are made. Upon contact the sampling frequency drops significantly.

3. Updates to the galen ADF model result in issues during runtime that slows down the sampling time. This was not originally the case until an edited model was left open in AMBF overnight. Reopening this model still has the model run at a very low frequency for some reason.

4. I am confused where to update and correctly change ADF model PID parameters. – I have changed the PID values in blender to different values and selected velocity control. Saving the model, and trying it in AMBF results in the model response becoming unexpected and slows the frequency down significantly. I am doing something inncorrectly.

5. When running the AMBF Galen model simulation, the terminal mentions that the Galen robot fails to load the plugin .so. I am unsure of this plugin's use (would this relay the force sensor data to me perhaps). The robot runs without this plugin, but if I fix the path to the plugin so it loads correctly, the AMBF simulation crashes on initialization with a segmentation error.

Further work will be done to resolve some these issues. Other issues are not as related to the project deliverables and will be removed from the task list. In the future more work towards identifying the AMBF model Galen will be done for the entire true system rather than as a mass spring damper. The actual robot in the Mock OR will also be identified, and the controller will be designed for real world application. The controller will be updated with designs to operate in cartesian space.