ME 315 SLP
Vibration Suppression Control of Robotic Arms

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Problem Statement

- Robotic arm at robotics startup - AXIBO:
  - 6-axis
  - BLDC motors
  - Harmonic reducers
- Initial Task:
  - Reduce vibrations faced by the arm at certain configurations and certain velocities

Approach

- As studied in ME 604:
    - Made a schematic of the arm
    - Computed singularities
- Conducted research on:
    - Harmonic drives - Transmission error
    - BLDC motors
    - Field-oriented control
- Concluded: Longest link (1m) affected the most by vibrations
- Proceeded to simulate assembly using **Simscape**

Modeling the Longest Link Assembly

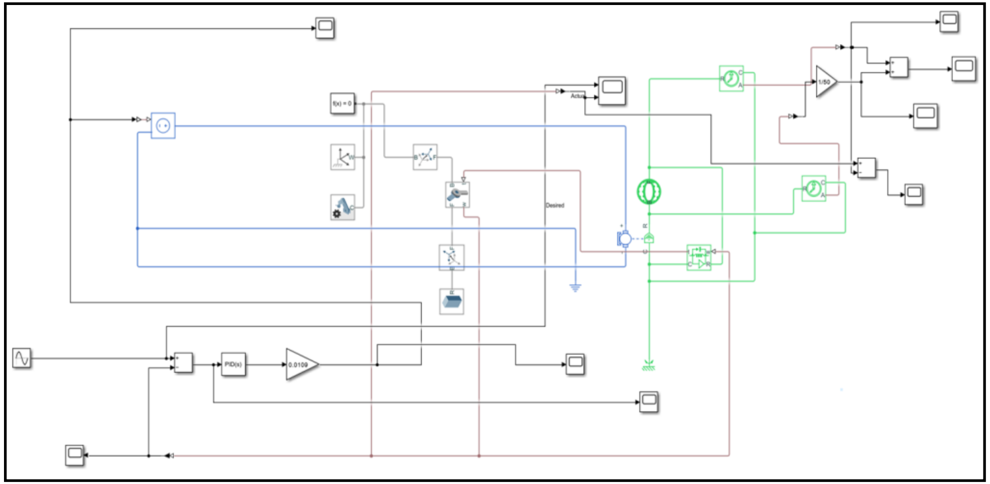

Fig: Simulation of entire assembly

- Simulation contains:
  - DC motor
  - Harmonic drive
  - Link (Al - $0.1*0.1*1\ m^3$)
  - PID control loop

Results

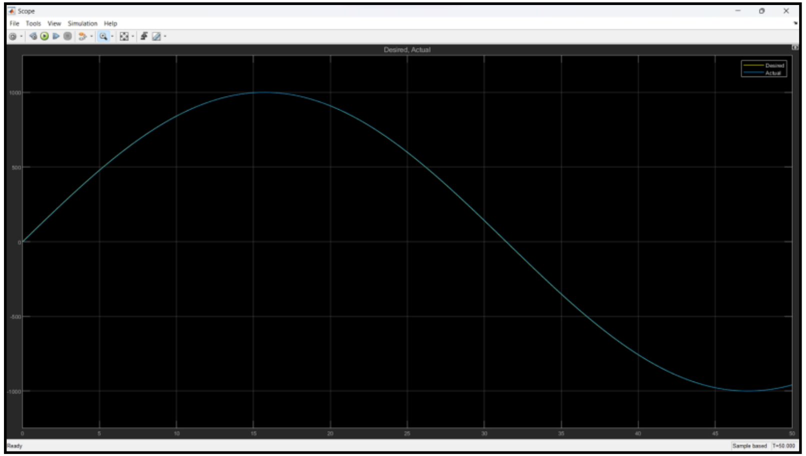

Fig: Velocity tracking

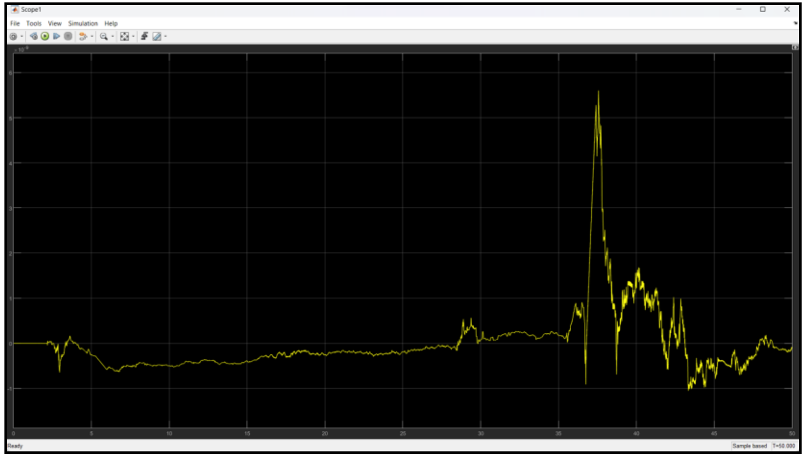

Fig: Transmission error

Discussion

- Vibration directly related to transmission error
    - Transmission error = Difference between input and output displacements of harmonic drive
- Transmission error insignificant: order of 1e-9 rad; not realizable in real world
- Studies inconclusive - we study harmonic drive separately

Modeling only Harmonic Drive

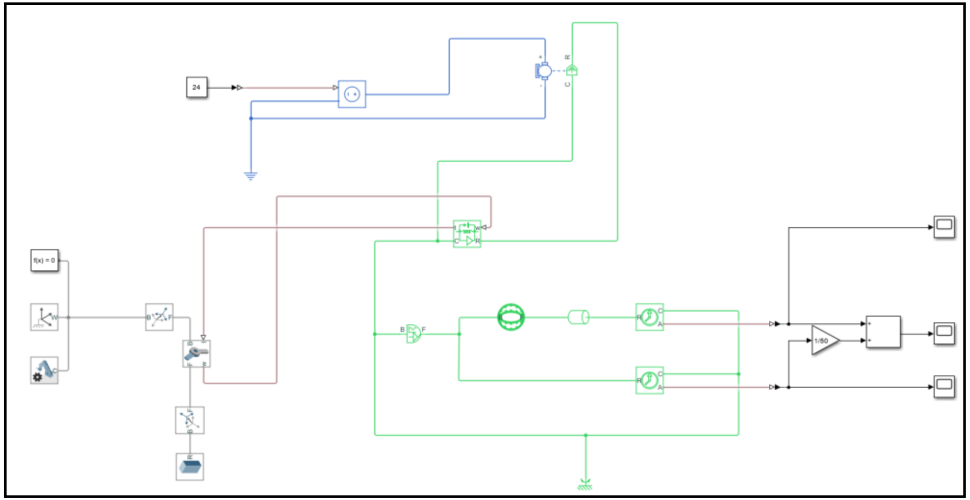

Fig: Simulation of harmonic drive

- Salient features:
  - Motor replaced with ideal velocity source (sinusoidal)
  - Harmonic drive isolated

Results & Discussion

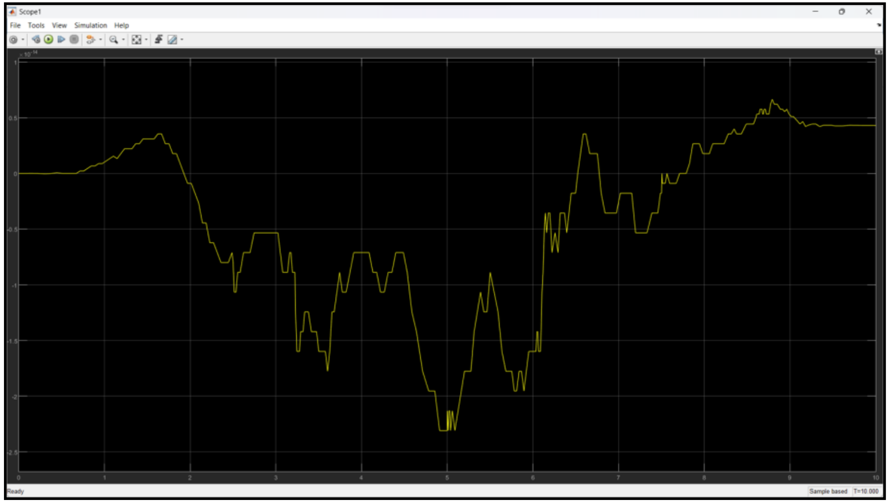

Fig: Transmission error

- Transmission error of the order of 1e-14 rad
- MATLAB precision - 16 digits
- Even increasing inertia/load does not have much effect on error
- Conclusion: Only harmonic drive unlikely to cause vibrations, need some non-ideality (introduced in form of rotational spring)

Modeling Harmonic Drive with Rotational Spring

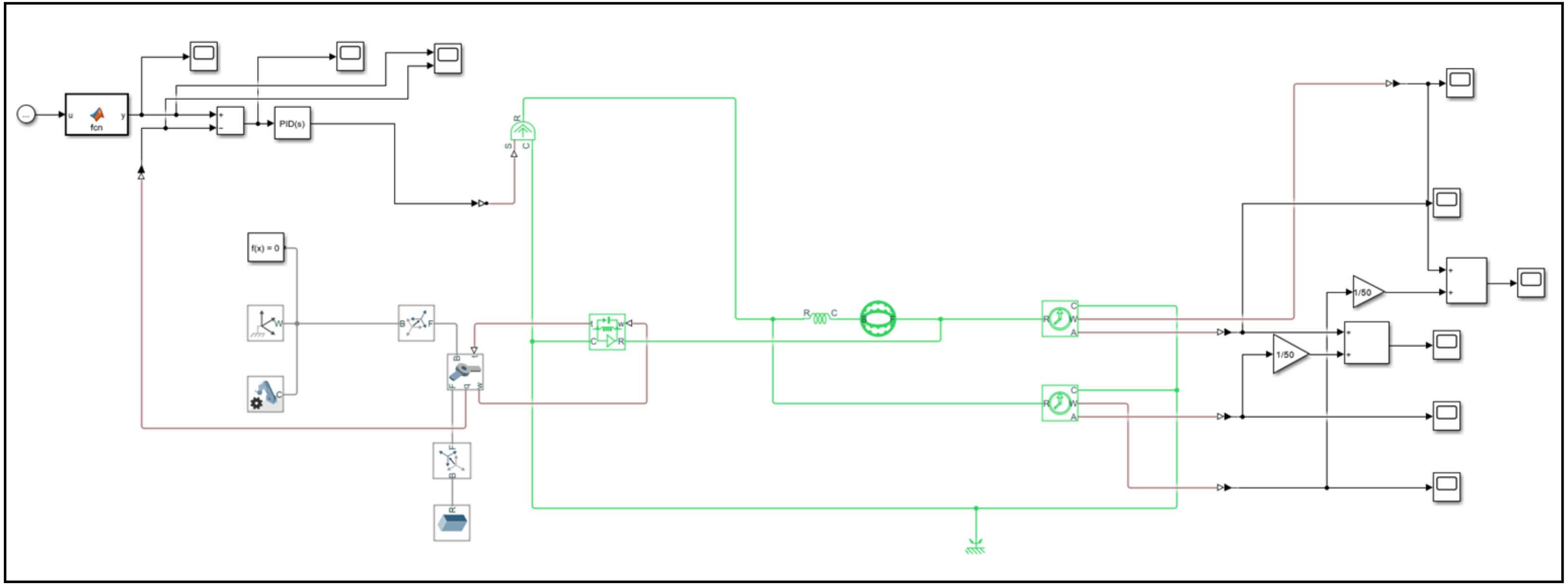

Fig: Simulation of harmonic drive with rotational spring

Results

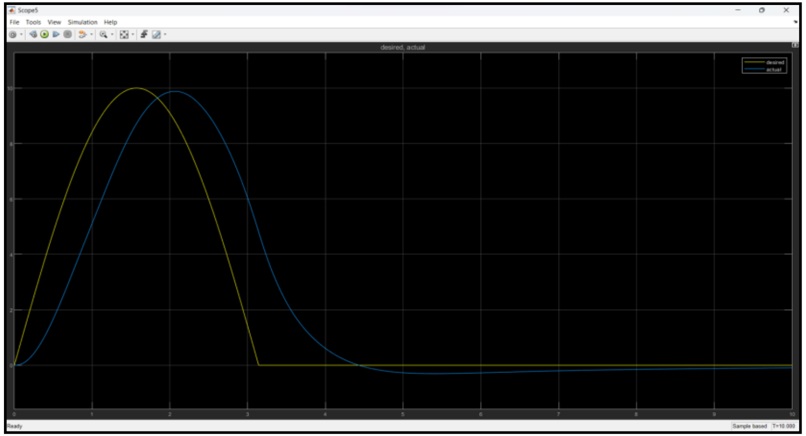

Fig: Angular position tracking

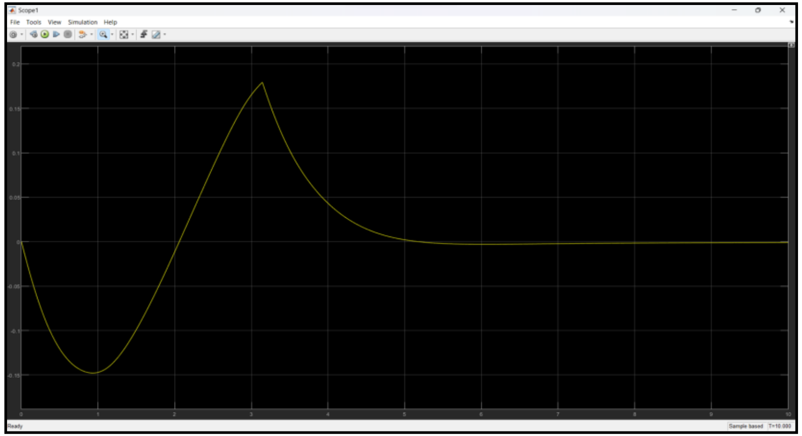

Fig: Transmission error

Discussion

- Rotational spring seemed promising
- Transmission error: order of 1e-1 rad, but due to input nature
- Still did not mimic real world scenario

Harmonic Drive Research

- Due to the harmonic drive element in Simscape not giving satisfactory results, we try alternate ways to model it
- *Xian Zhang, Tao Tao, Gedong Jiang, Xuesong Mei, Chuang Zou.* **‘A Refined Dynamic Model of Harmonic Drive and Its Dynamic Response Analysis’** describes a model for the harmonic drive which takes into account the friction, stiffness, and transmission error
- *Makoto Iwasaki, Hiroyuki Nakamura.* **‘Vibration Suppression for Angular Transmission Errors in Harmonic Drive Gearings and Application to Industrial Robots’** describes a two-axis inertia system and a vibration suppression controller, shown on the next slide.

Model Described in Paper

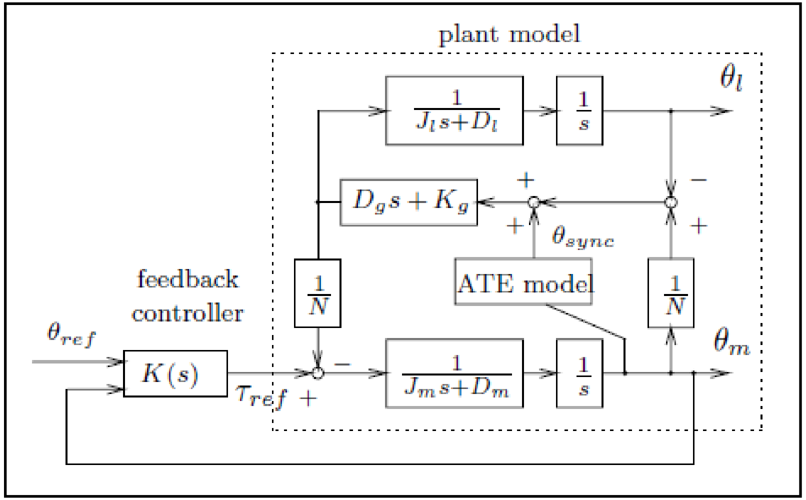

Fig: Two inertia axis system (plant model)

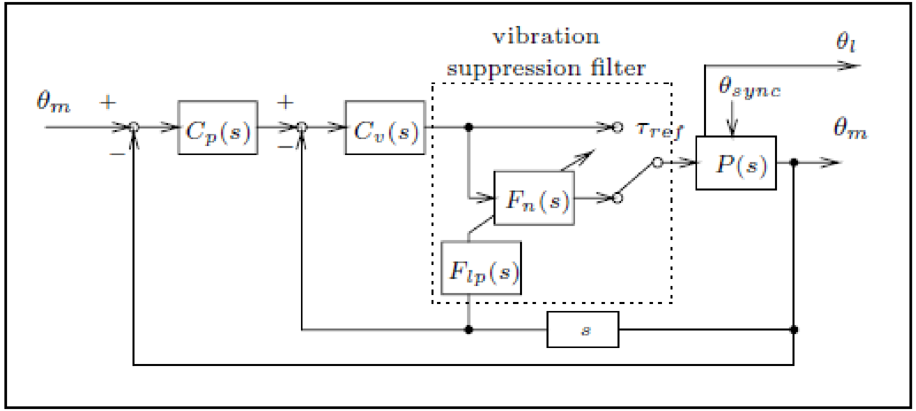

Fig: Vibration suppression controller

Model Described in Paper (Cont.)

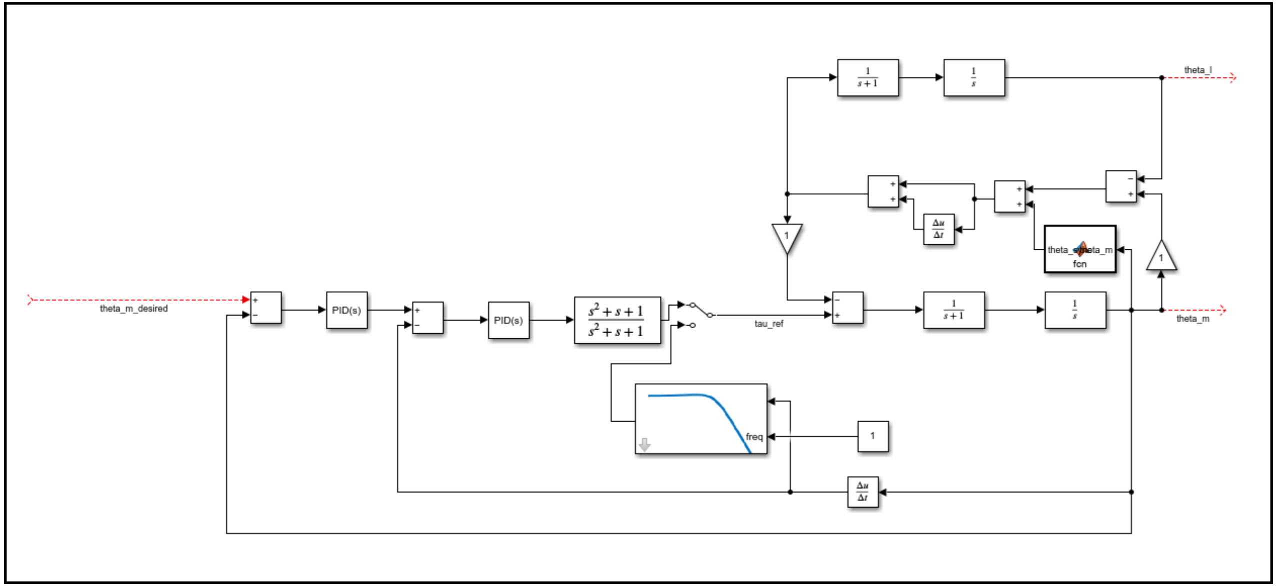

Fig: Simulink model of entire system

Model Described in Paper (Cont.)

- Controller consists of:
  - Variable notch filter to reduce vibrations
  - Low-pass filter to remove sensor noise
  - Switching mechanism to control activation of notch filter
- Model tested for random inputs, but exact parameter values unknown
- Company already using low-pass filter; upon recommendation to use notch filter, vibrations in robotic arm reduced considerably

Modeling the Updated Longest Link Assembly

- Though vibration problem was somewhat solved, a simulation base was needed
- Created an updated model with:
  - DC motor
  - Harmonic drive
  - Angular position tracking
  - Rotational spring

Modeling the Updated Longest Link Assembly (Cont.)

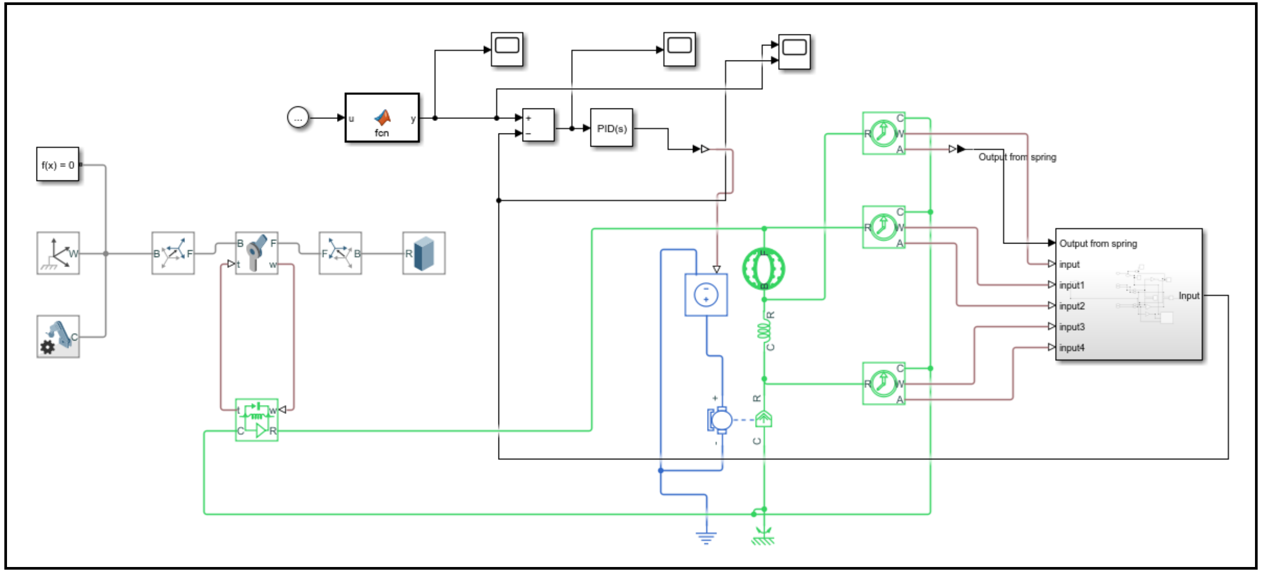

Fig: Updated simscape model

Results

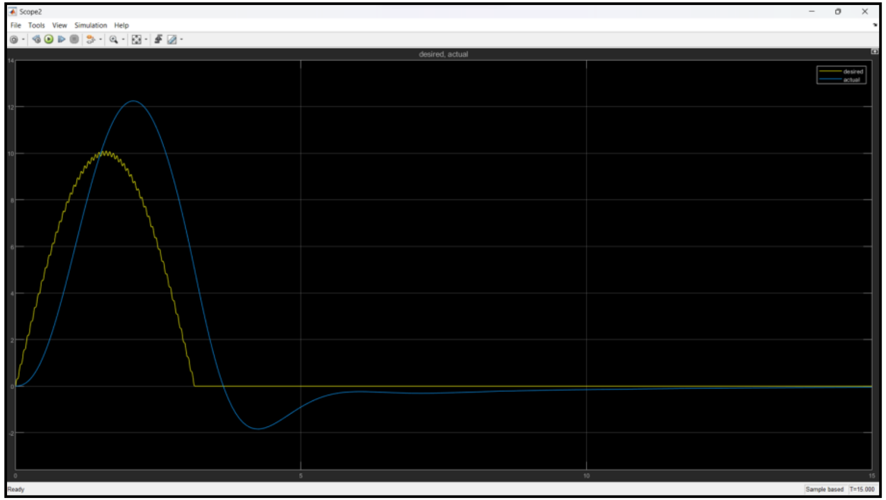

Fig: Angular position tracking

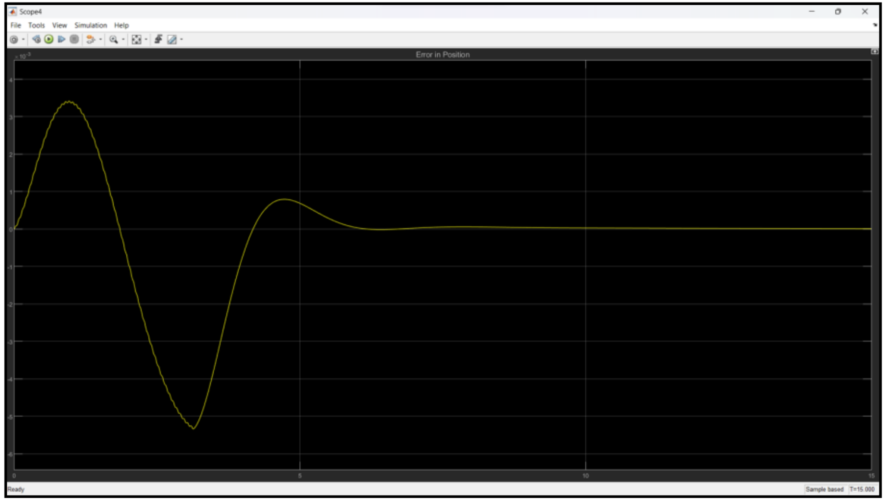

Fig: Transmission error

Discussion

- Position feedback was taken right from motor instead of revolute joint (as done before) which resembles the real world scenario
- Transmission error significant, but still no vibrations
- Conclude that only harmonic drive may not be the cause of vibrations, have to introduce BLDC motor as well

Modeling the BLDC Motor

- Studied BLDC motors and field oriented control
- Referred to readymade Simulink models of BLDC motors to understand better
- Model needed new components like three-phase inverter, the BLDC motor itself, commutation logic, PWM controller, etc.

Modeling the BLDC Motor (Cont.)

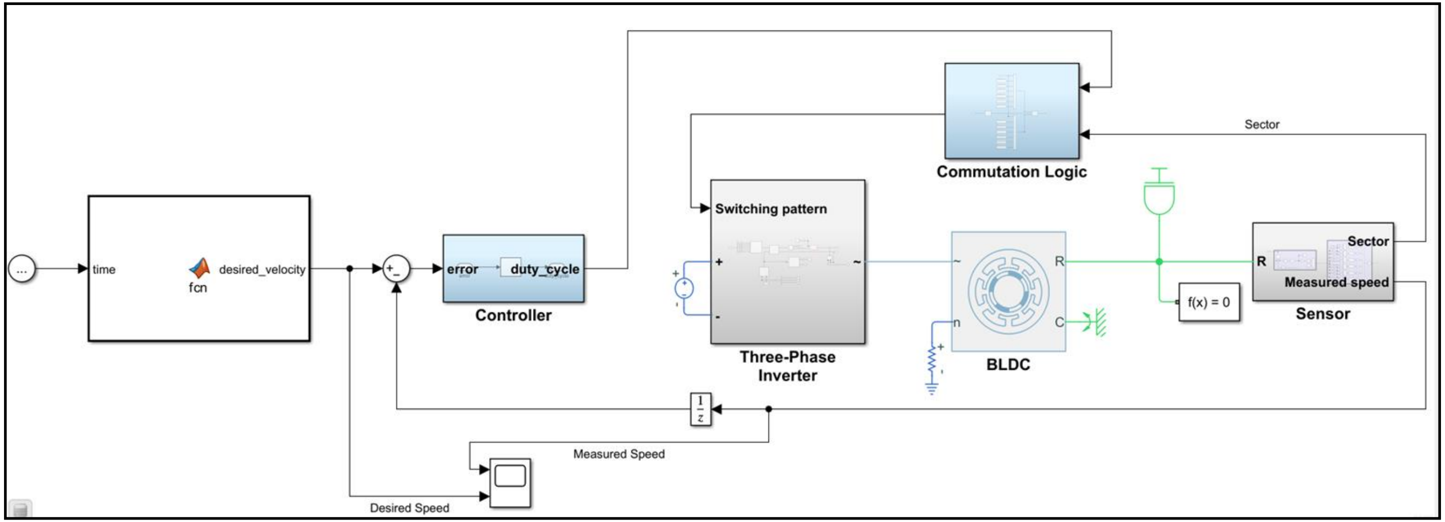

Fig: Velocity tracking model with BLDC motor

Results & Discussion

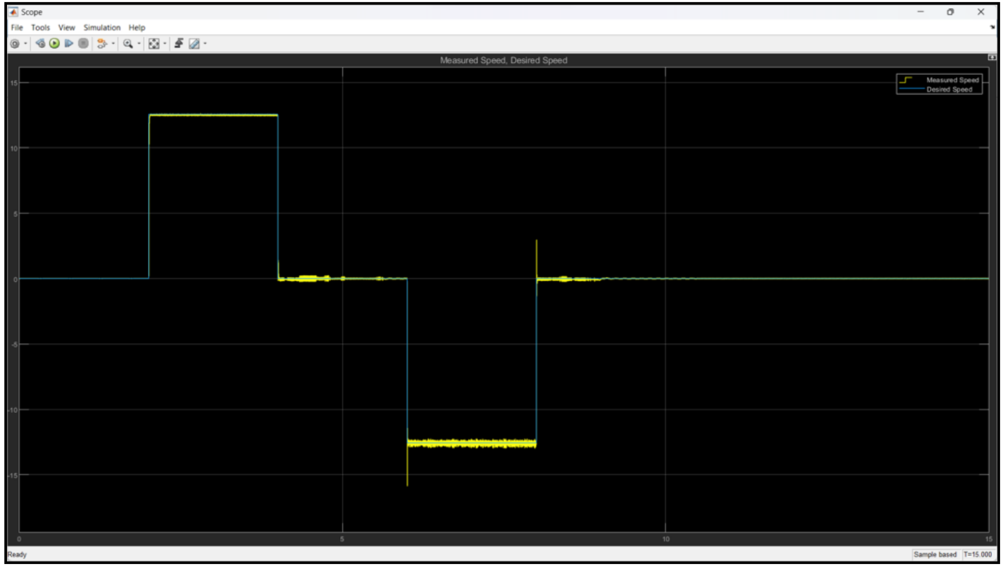

Fig: Velocity tracking

- BLDC motor even without harmonic drive and added noise shows vibrations
- Next step: combine BLDC motor with harmonic drive

Modeling BLDC Motor with Harmonic Drive & Load

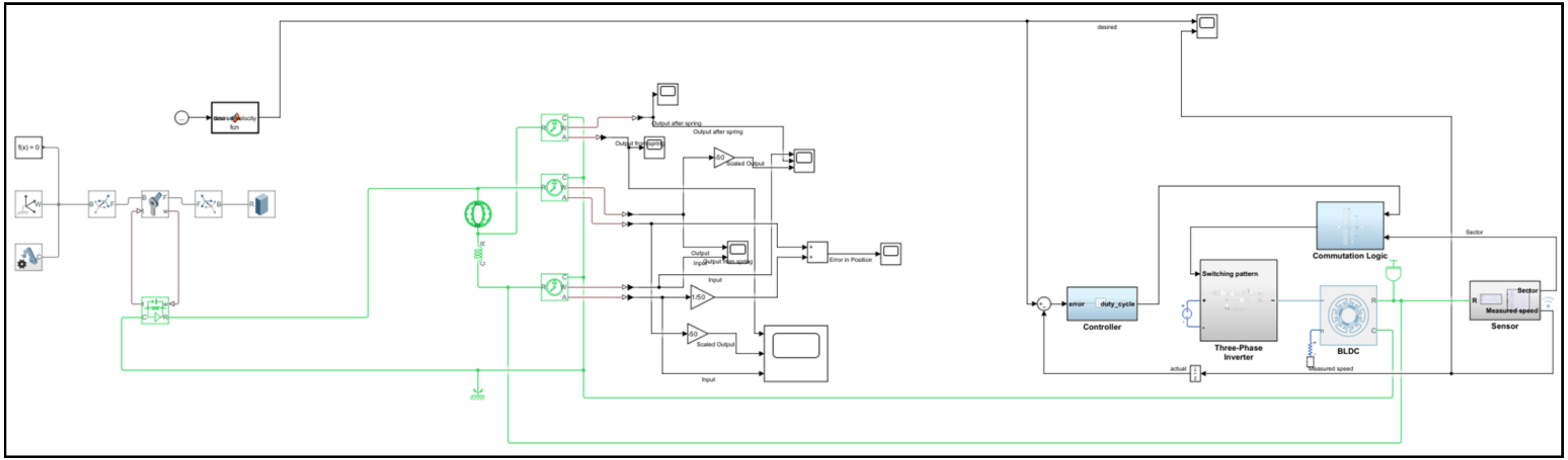

Fig: Simscape model of entire assembly using BLDC motor, harmonic drive and load

Results

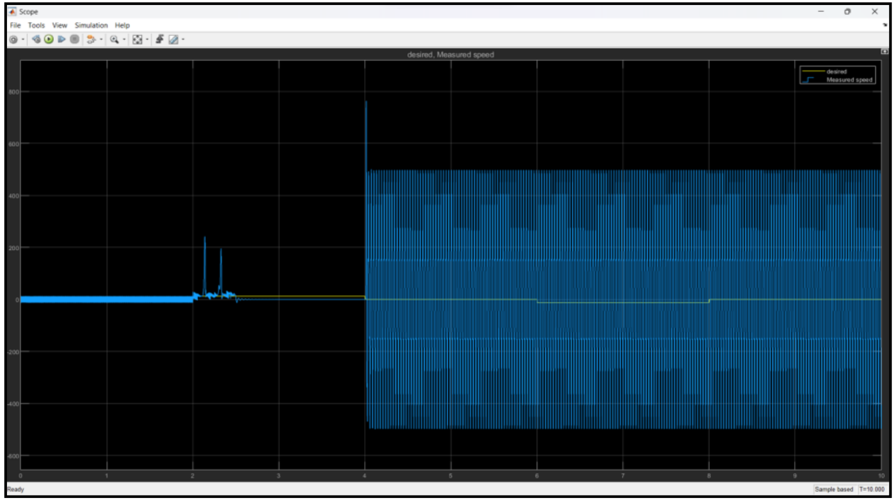

Fig: Velocity tracking

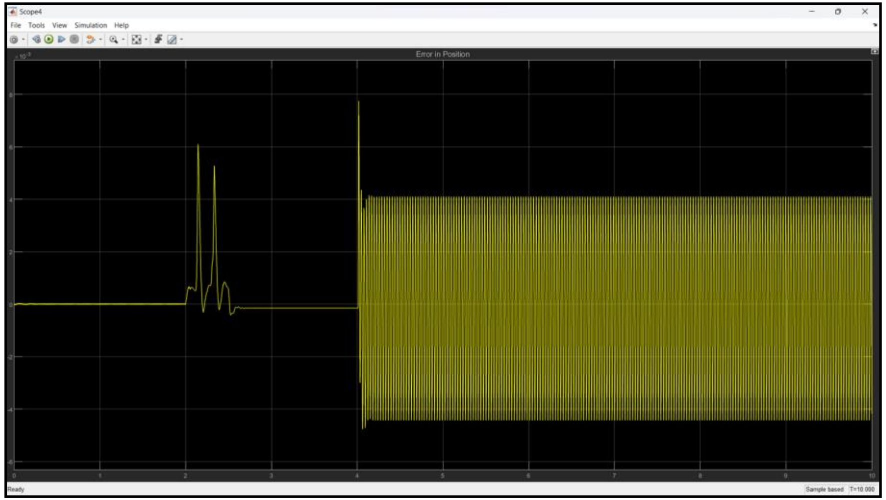

Fig: Transmission error

Discussion

- Transmission error: order of 1e-3 rad, significant enough to cause vibrations
- Velocity characteristics haywire
- Notch filter best bet

Input Shaping for Vibration Reduction

- Input shaping: feedforward method to reduce vibrations in robotic arms, especially at end effector
- *Dan Kielsholm Thomsen, Rune Soe-Knudsen, Ole Balling, Xuping Zhang.* **‘Vibration control of industrial robot arms by multi-mode time-varying input shaping’** provides a comprehensive procedure to implement input shaping for a robotic arm
- Multi-Mode Time-Varying Input Shaping Technology (TVIST) was established as the best way to dampen vibrations

Input Shaping Model

- Components: DC motor, harmonic drive, rotational spring, rotational damper, aluminium bar, PID control loop
- Velocity tracking done via PID control loop
- Loads applied at end of aluminium bar
- To mimic real world, some random noise was also added

Input Shaping Model (Cont.)

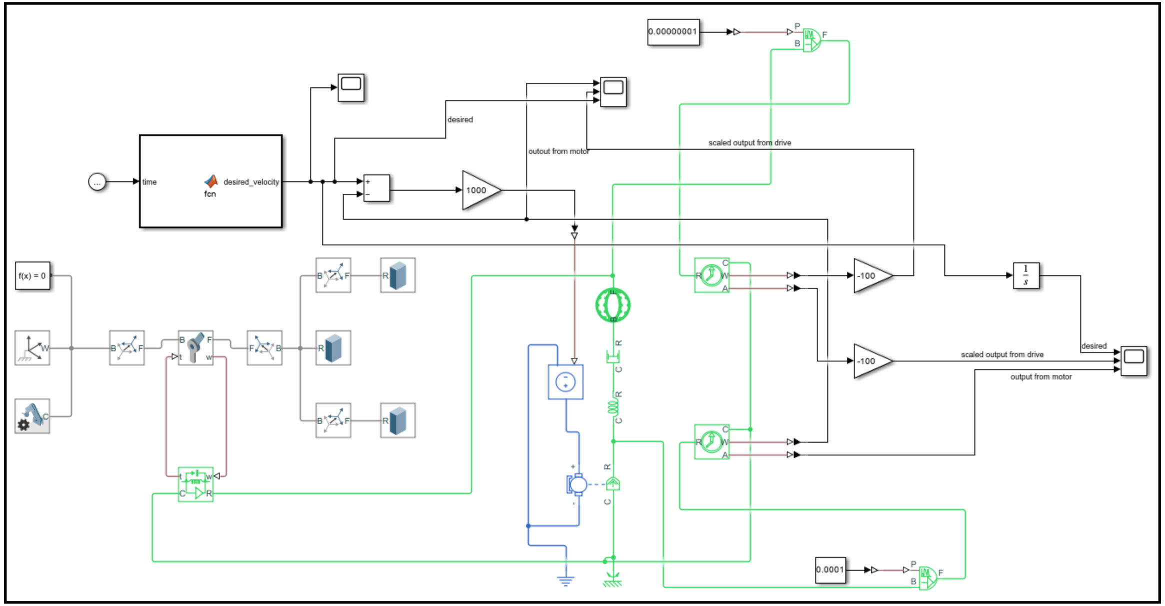

Fig: Combined model for studying input shaping

Results

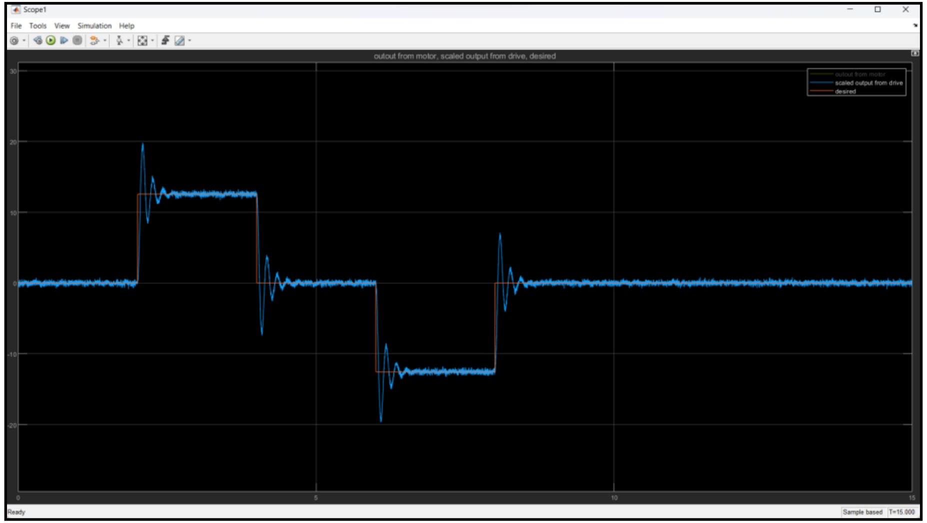

Fig: Velocity tracking

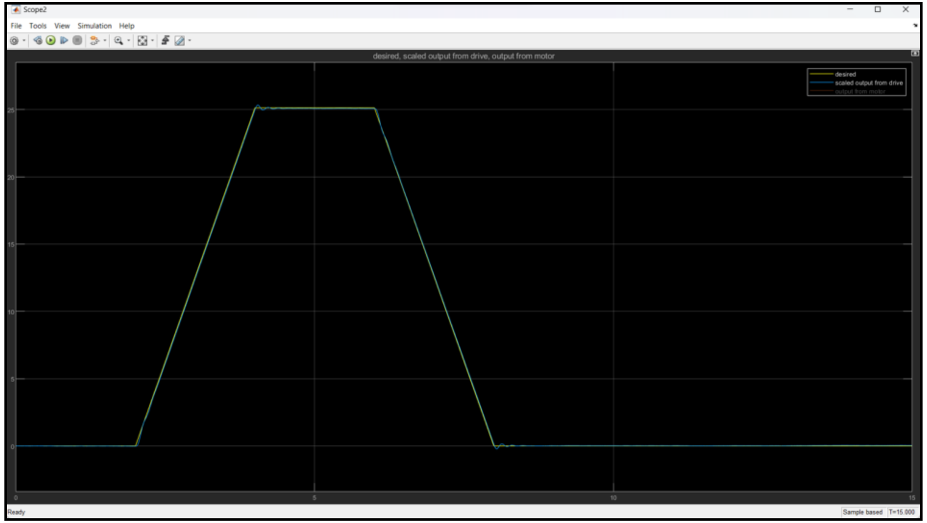

Fig: Desired (yellow) and actual (blue) positions

Results & Discussion

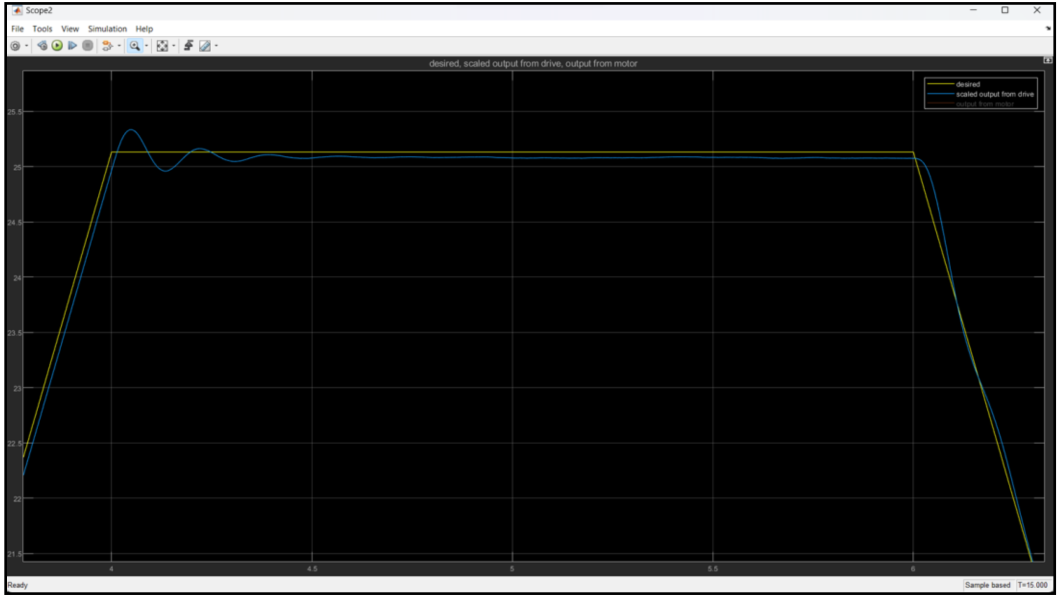

Fig: Desired and actual positions (zoomed in)

- Results match the real-world behaviour exactly
- Next steps: Apply multi-mode TVIST and see if oscillations cease

Robot Hardware Testing

- Since the startup had products lined up, they needed help testing the robot software and hardware
- Assembled and tested hardware at the company warehouse and performed limit tests and speed tests to ensure the pieces were fit to go to market
- Performed some basic communication and app based tasks

Communication System for Robot

- Similar to pub-sub in ROS, a server for publishing and a client for subscribing was set up using the pyzmq library
- Rate of publishing, message filter, etc. can be changed
- An application was set up using Streamlit library on the local machine
- The data received by the client was plotted against time, and the plot could be started and stopped at any time using the buttons
- Finally, an interface was created with buttons for various tests of the robot, which prints the status of the robot every 1 second

Server & Client

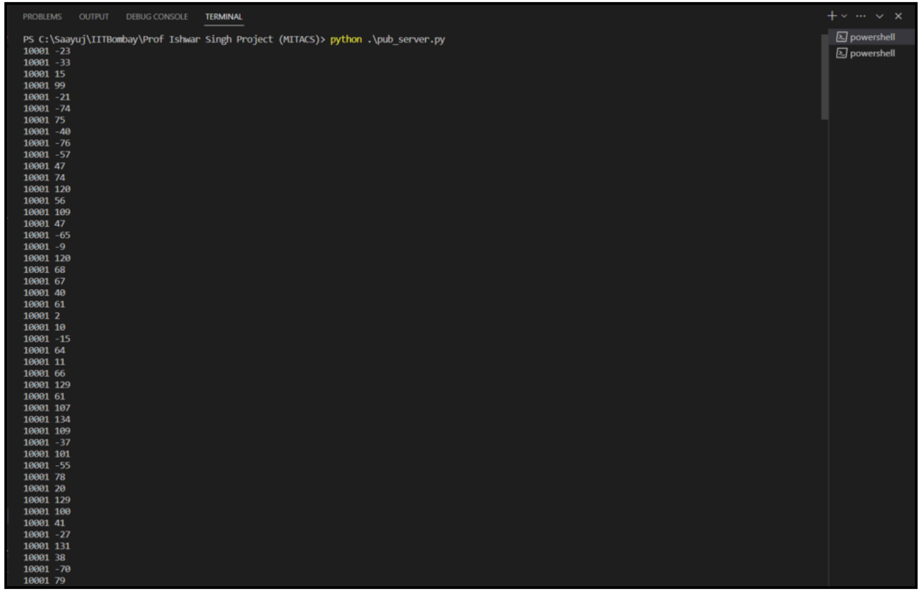

Fig: Server publishes data in this format

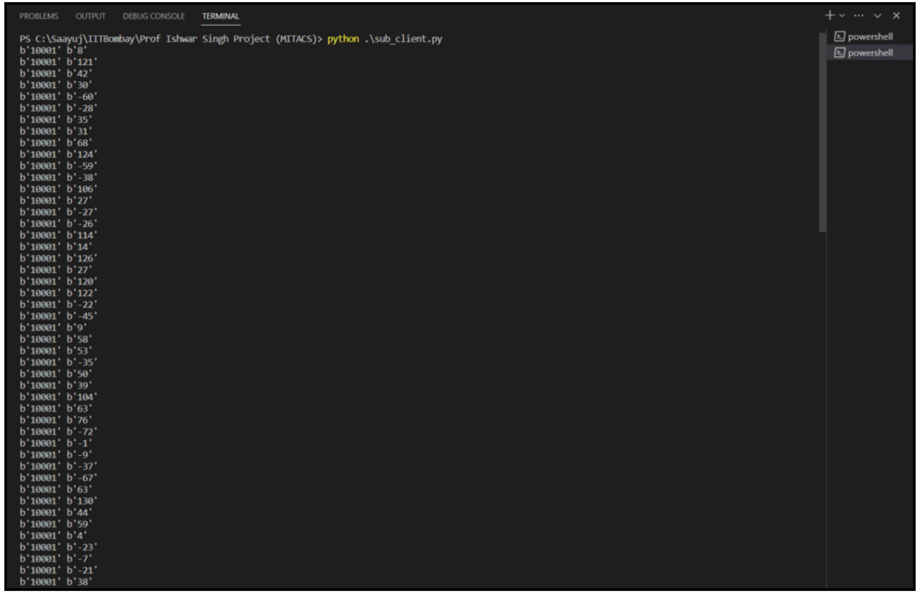

Fig: Client receives data in this format

Application

Fig: Constantly updating plot with data from server

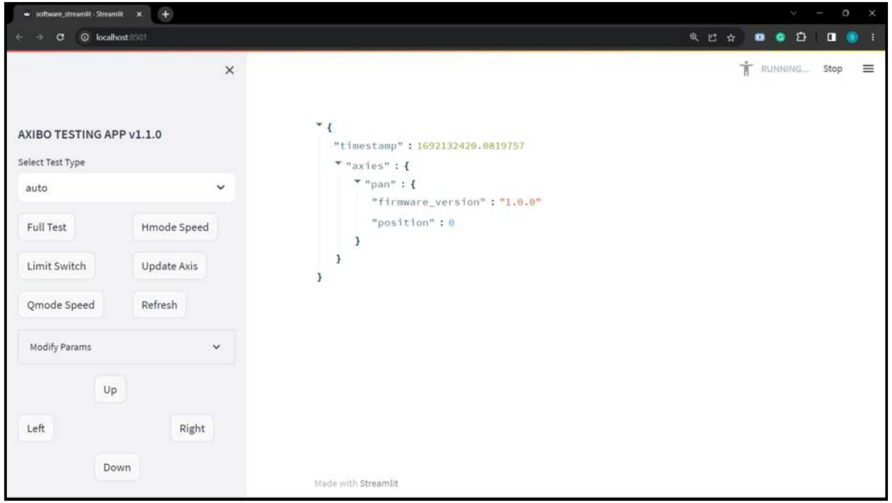

Fig: Testing application