MOTION CONTROL INTERN – FINAL PRESENTATION

SESHA CHALA

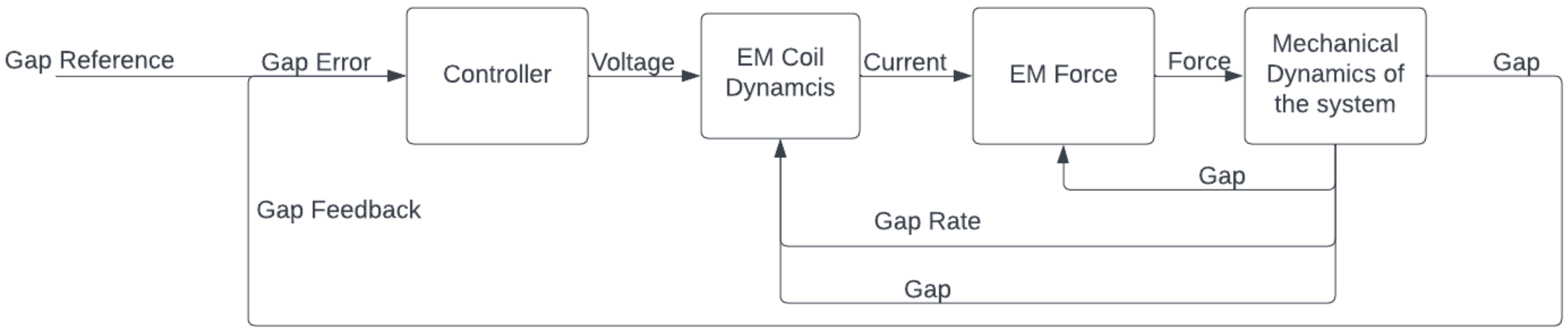
INTERN DURATION: 06/20/2022 TO 08/19/2022

OVERVIEW

- Goals
- Supervisory Control for Levitation
- Single EM engine control simulations
- Guidance Control underdamping Investigation
- Conclusion and Future Work

Motion Control for Cargo Pilot Project: Levitation and Guidance Control

Baseline Control System Diagram



Observation:

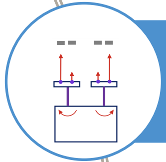
The problem is not about controlling the gap but controlling multiple gaps with dynamics that are often coupled.

Contributions

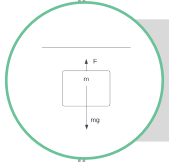
- Levitation Control: Supervisory control for current matching at the bogie level to improve engine efficiency.
- Control Architecture: EM Engine Control Modeling and a detailed linear gap control architecture and its limitations.
- Guidance Control: Investigation of under-damping in guidance control and MIMO modelling of the guidance bogie
- Propulsion Motor Control: Explored FOC and phase angle estimation.

OVERVIEW

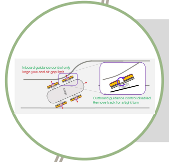
Goals



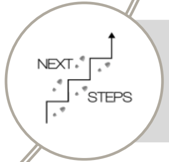
Supervisory Control for Levitation



Single EM engine control simulations

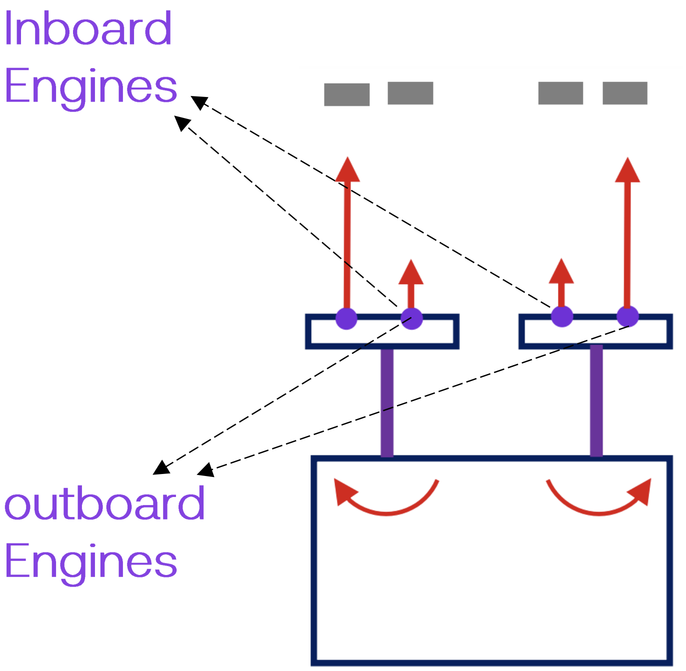


Guidance Control underdamping Investigation

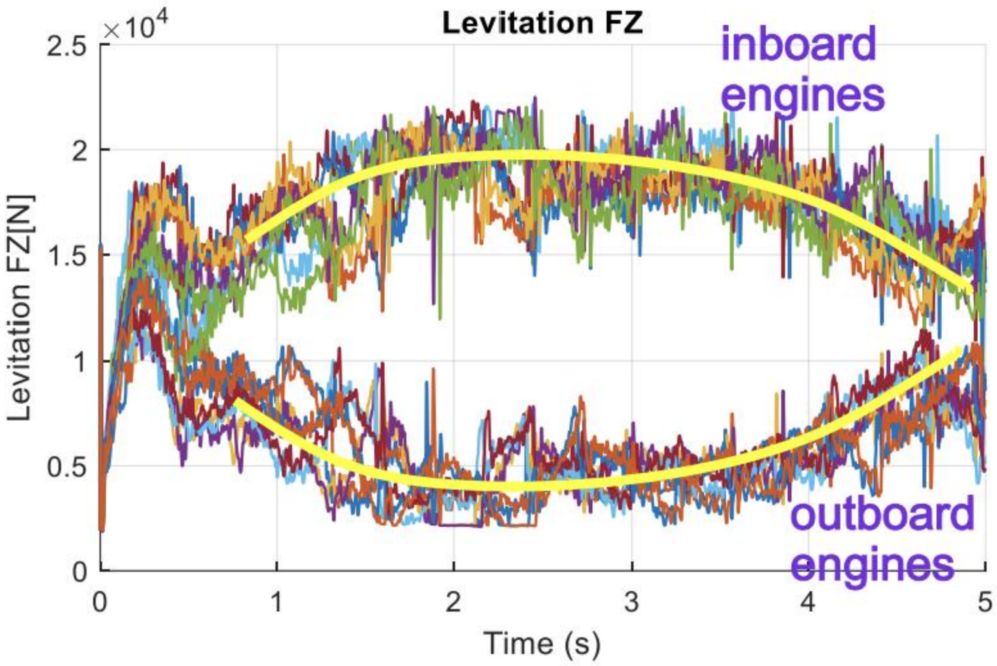


Conclusion and Future Work

Problem: Engine-level Levitation Control gives uneven forces



Front View of the Vehicle



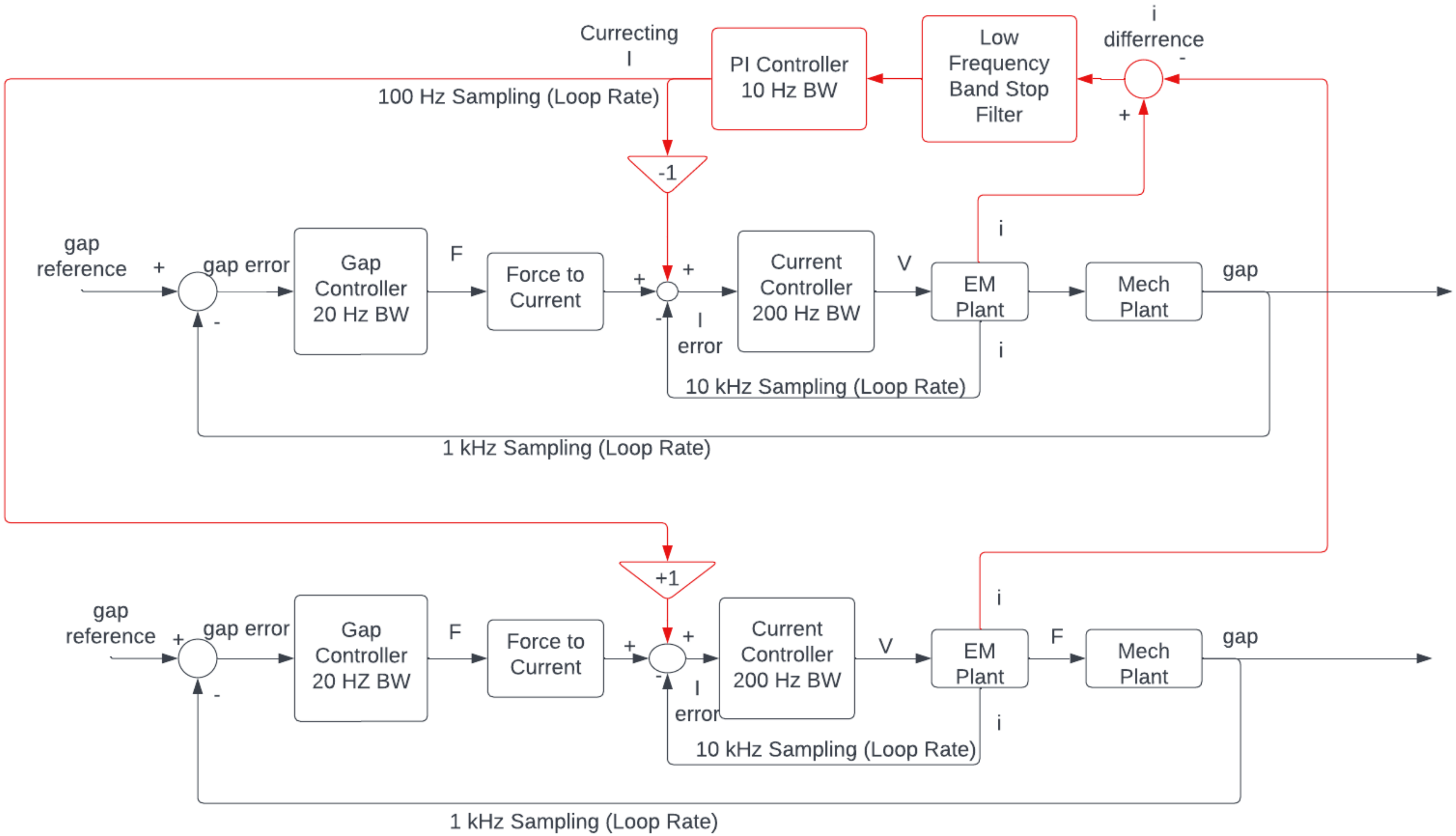
Levitation Forces from 16 engines

Solutions:

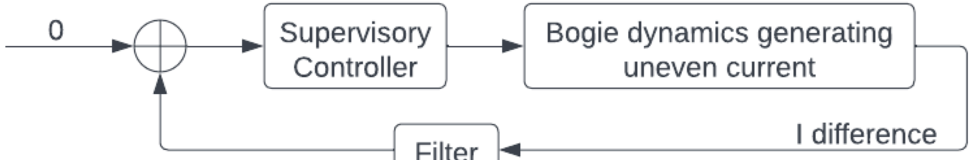
- Partially Centralized Control: Average the gap feedback
- **Bogie-level Supervisory Control**: Inject correcting current disturbances.

Supervisory control: force matching at bogie level

- Feedforward Control technique: Introducing “middle” loop closure using current difference



Supervisor Design Details



Supervisory controller in block diagram in standard form

Supervisory Controller:

1. Make steady state uneven current to zero.
2. Correct for uneven current signals in a definite frequency range (Bandwidth).

Filter:

1. Filter the low frequency uneven current signals from the feedback.
2. Make the gap-control have uneven currents when there are low-frequency track induced disturbances.

PI Supervisory Controller:

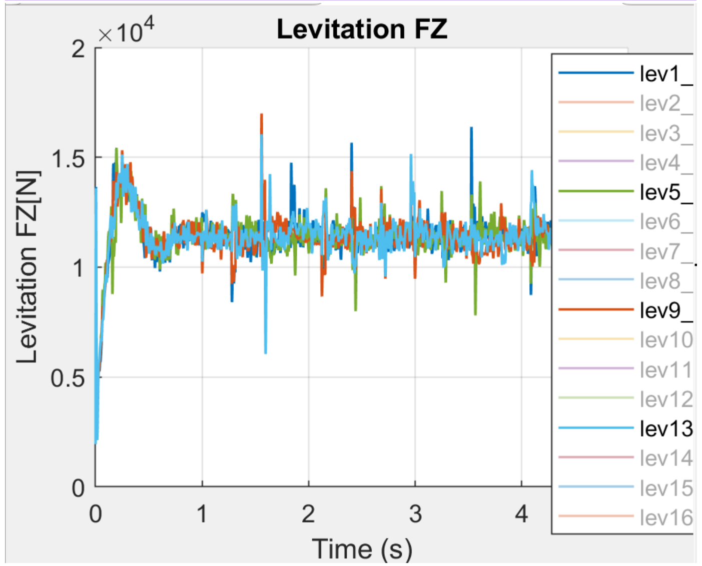
$$K_p = 0.5 \qquad \left[\because I_1' = I_1 - \left(\frac{I_1 - I_2}{2}\right), \quad I_2' = I_2 + \left(\frac{I_1 - I_2}{2}\right)\right]$$

$$\omega_{BI} = 2\pi \times 10 \qquad [\text{Function of desired bandwidth}]$$

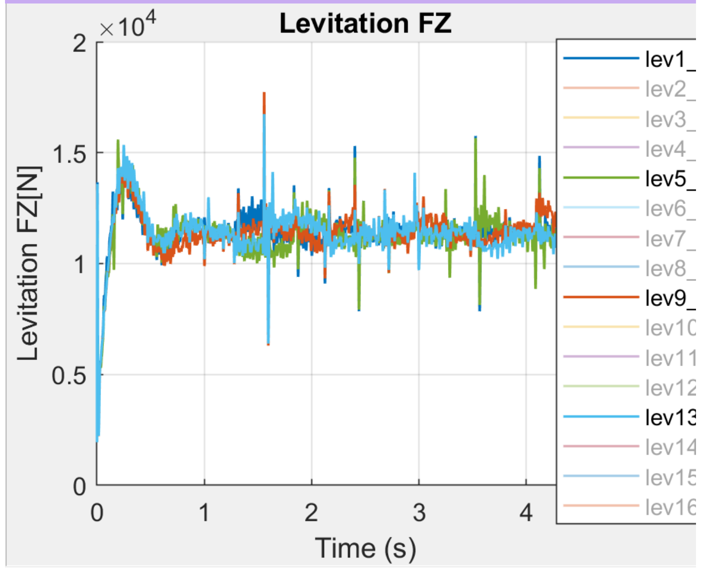
$$\therefore \text{PI Controller: } K_p\left(1 + \frac{\omega_{BI}}{s}\right)$$

Supervisor and PCC results comparsions

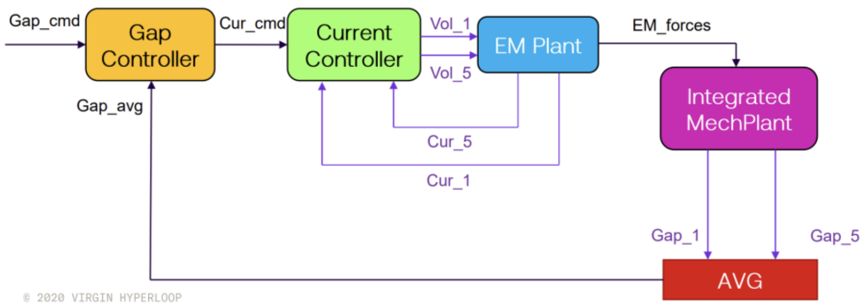
Supervisory Control



Partially Centralized Control



Partially Centralized Control Architecture

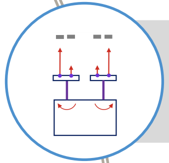


Advantage of Supervisory Control

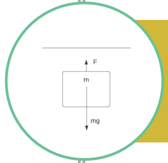
- Flexibility to tune the bandwidth of the supervisor to limit its action to a range of frequencies.
- The architecture allows incorporating engine level fault-detection-isolation/fault-tolerance in the control system.
- Supervisor + Gap Controller dampens bogie vibrations but PCC + Gap Controller can not.
  - Gap Controller generates uneven currents at bogie vibration frequency to dampen the bogie roll vibrations.
  - Because of the bandwidth limitation of the supervisor, the high frequency uneven current signals are not damped.
  - The roll vibrations are not perceived by the gap controller in PCC architecture as gap is averaged.

OVERVIEW

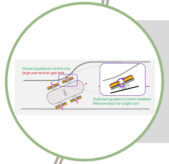
Goals



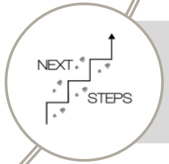
Supervisory Control for Levitation



Single EM engine control simulations



Guidance Control underdamping Investigation



Conclusion and Future Work

A Single (hanging) EM engine: Model Parameters

EM Coil Dynamics:

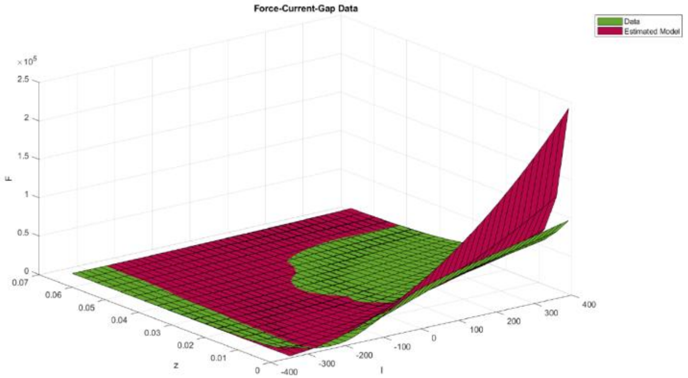
$$V = RI + \frac{2K}{z}\dot{I} - 2K\frac{I}{z^2}\dot{z} \xrightarrow{\text{Small Perturbation}} V = RI + L\dot{I} - b_z\dot{z}$$

where, $L = \dfrac{2K}{z_N}$ $\quad b_z = 2K\dfrac{I_N}{z_N^2}$

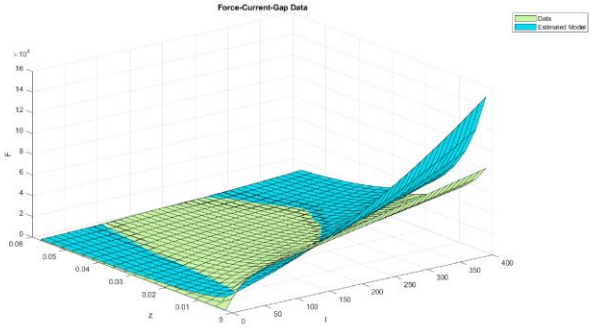
EM Force Model:

$$F = K\left(\frac{I + I_0}{z + z_0}\right)^2 \xrightarrow{\text{Small Perturbation}} F = k_I I - k_z z$$

where, $k_I = 2K\dfrac{I_N + I_0}{(z_N + z_0)^2}$ $\quad k_z = 2K\dfrac{(I_N + I_0)^2}{(z_N + z_0)^3}$



Levitation Engine Data and Model



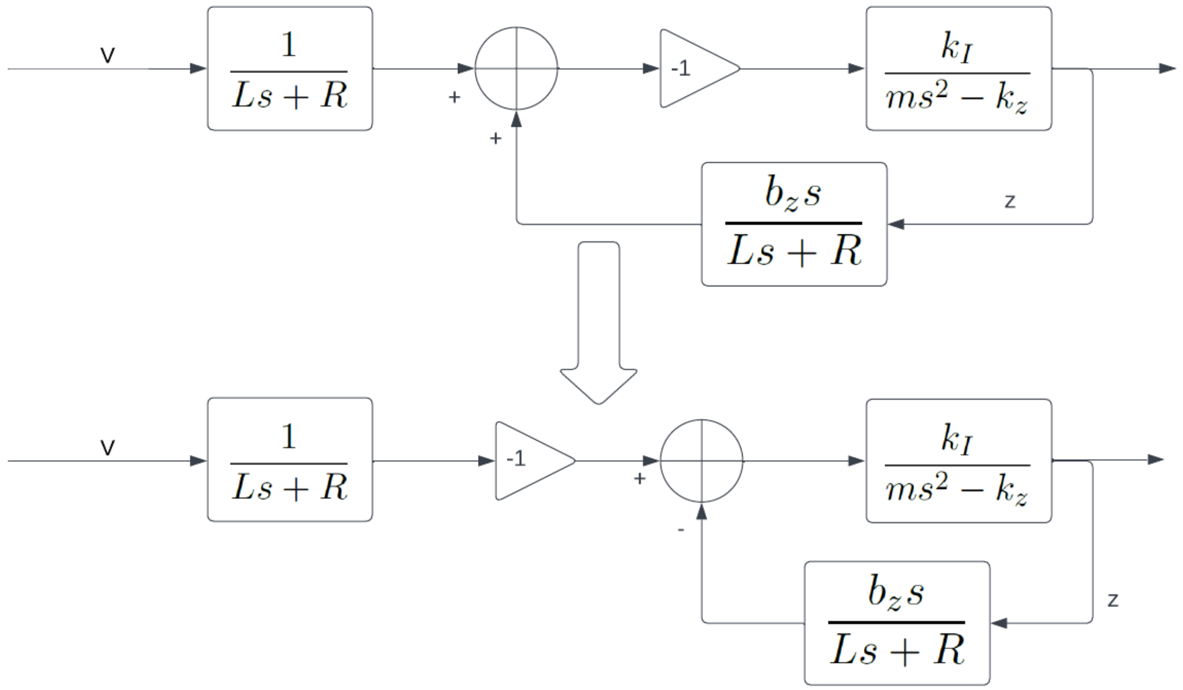
Guidance Engine Data and Model

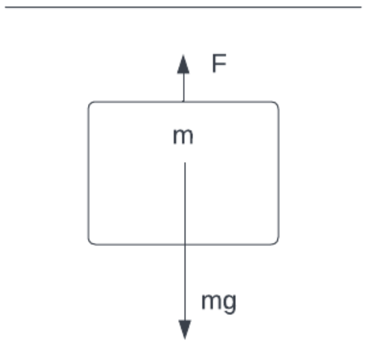
Engine	K	I_0	z_0	R
Guidance	2.1247×10^{-4}	165.0383	0.0192	0.8
levitation	3.1863×10^{-5}	372.1653	0.0079	0.8

Model Parameters estimated from cargosim lookup tables

A Single (hanging) EM engine: Equations of Motion

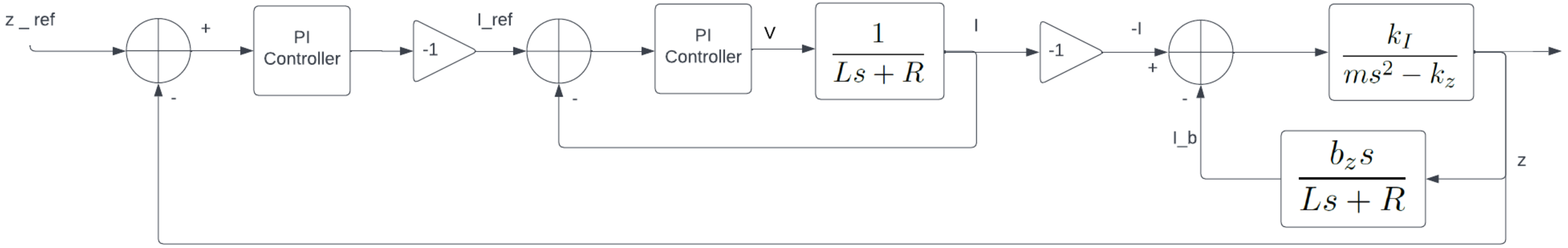
$$I = \frac{1}{Ls+R}V + \frac{b_z s}{Ls+R}z \qquad z(s) = -\frac{k_I}{ms^2 - k_z}I(s)$$

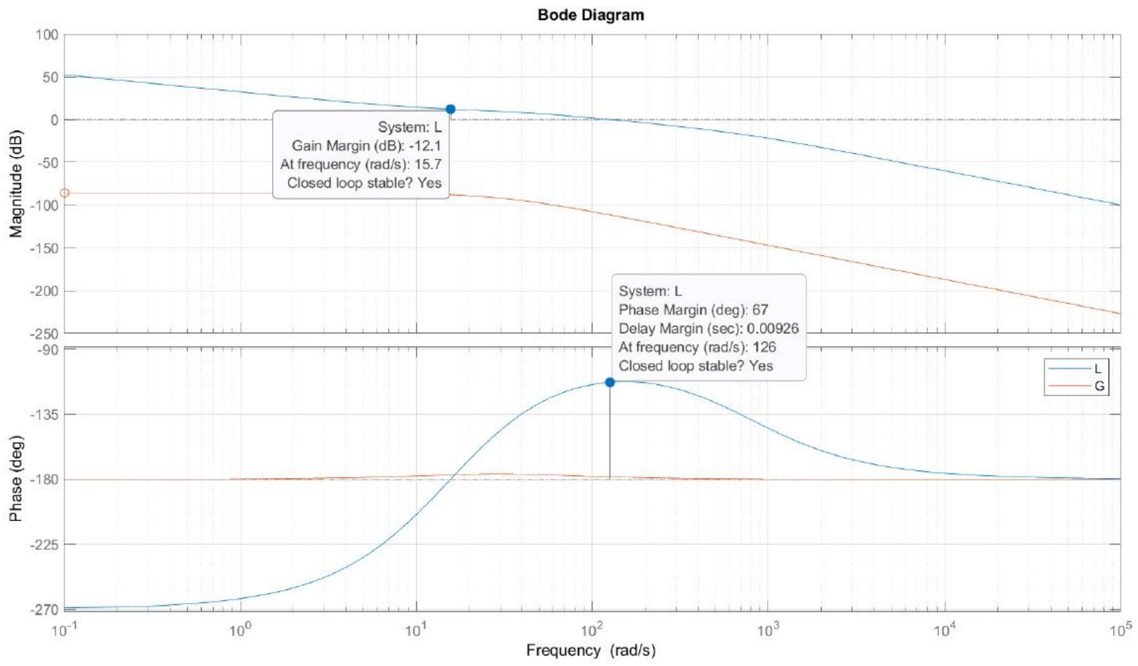


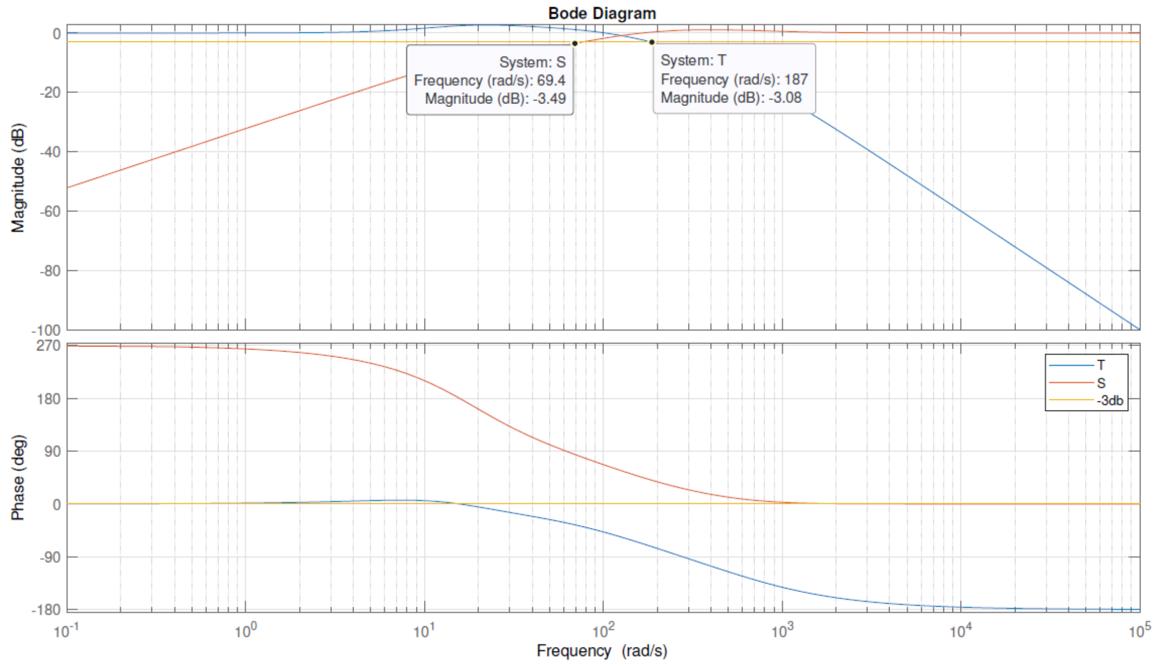


- 200 Hz bandwidth current controller
- 20 Hz bandwidth Gap Controller with for the current to gap plant with ‘back current’ as feedback.

A Single (hanging) EM engine: Control Architecture



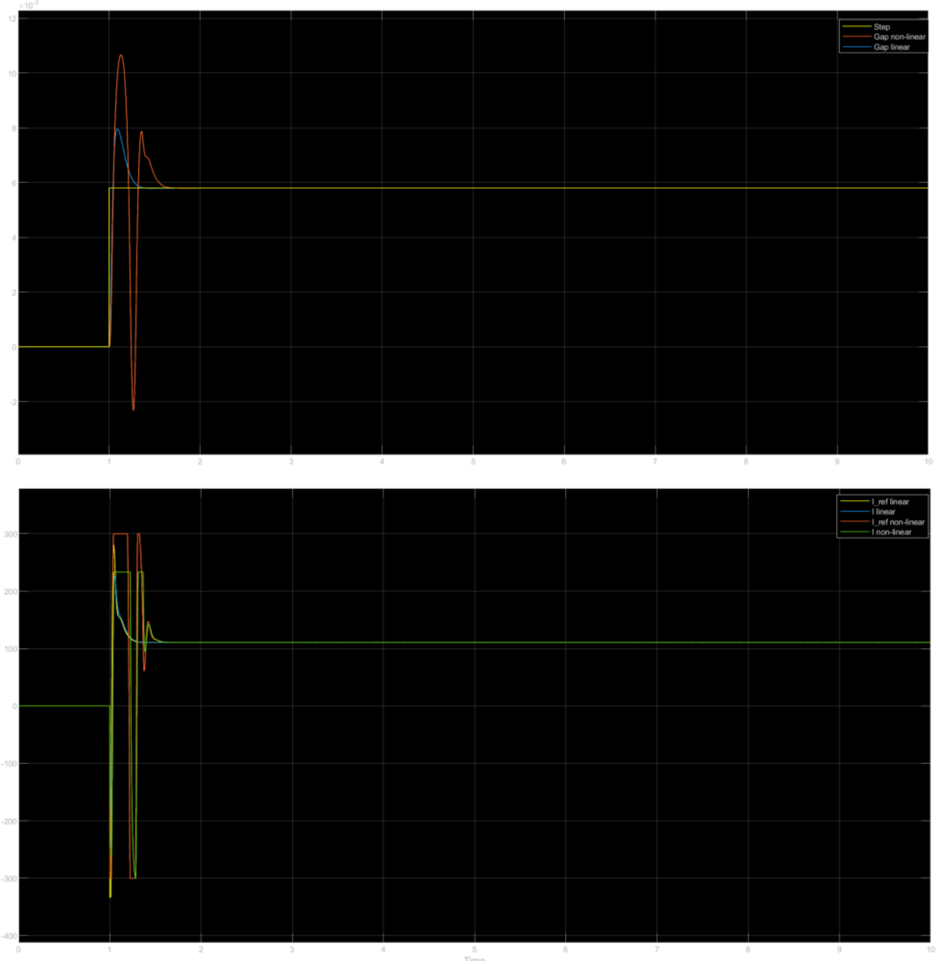




Validating the linear design:

Response to 5 mm Step reference

Response 5.85 mm Step reference

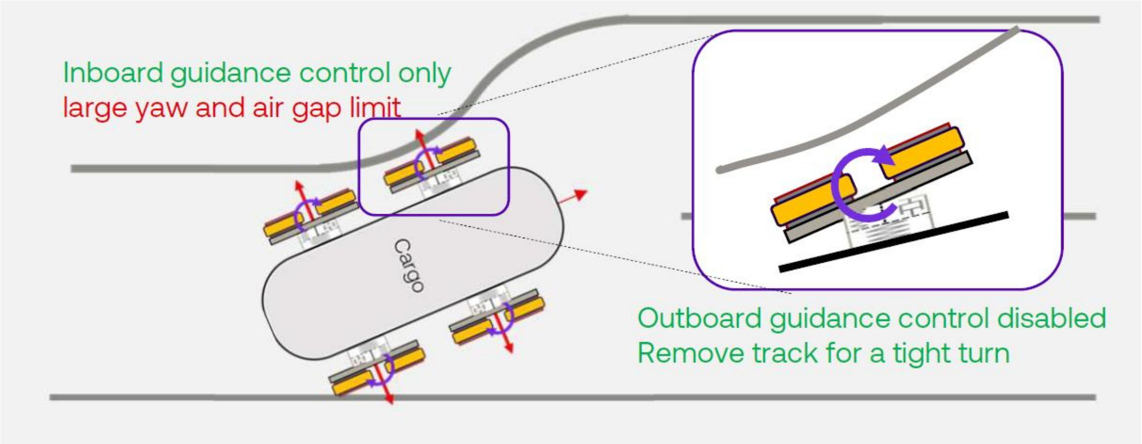


Maximum back-current is close to 10% of the maximum current input.

OVERVIEW

- Goals
- Supervisory Control for Levitation
- Single EM engine control simulations
- **Guidance Control underdamping Investigation**
- Conclusion and Future Work

Guidance Control: Bogie level planar dynamics modeling



Bogie Dynamics:

$$m_b\ddot{y}_b = -F_1 - F_2 + F_b - k_y y_b - b_y \dot{y}_b + k_y y_p + b_y \dot{y}_p$$

$$J_b\ddot{\psi}_b = F_1 L - F_2 L - k_\psi \psi_b - b_\psi \dot{\psi}_b + k_\psi \psi_p + b_\psi \dot{\psi}_p$$

Payload Dynamics:

$$m_p\ddot{y}_p = F_p + k_y y_b + b_y \dot{y}_b - k_y y_p - b_y \dot{y}_p$$

$$J_p\ddot{\psi}_p = k_\psi \psi_b + b_\psi \dot{\psi}_b - k_\psi \psi_p - b_\psi \dot{\psi}_p$$

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} 1 & -L \\ 1 & L \end{bmatrix} \begin{bmatrix} y_b \\ \psi_b \end{bmatrix} \implies \begin{bmatrix} y_b \\ \psi_b \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2L} & \frac{1}{2L} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$$

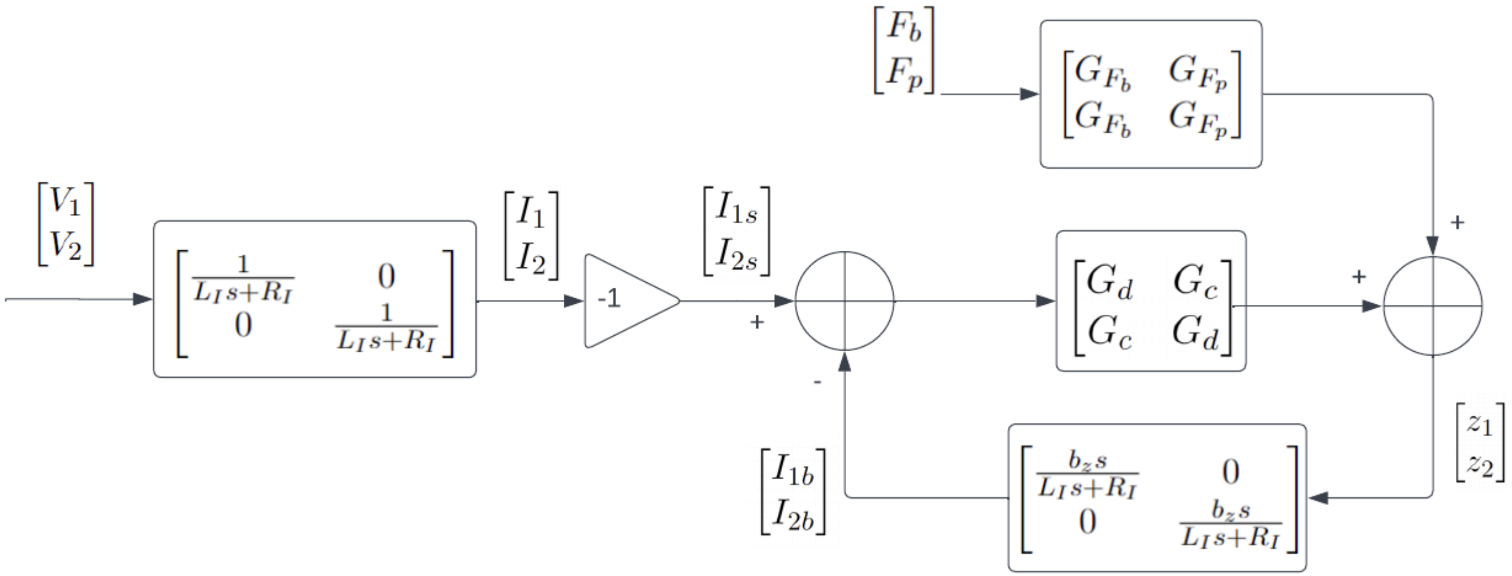
MIMO guidance bogie model:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = -\begin{bmatrix} G_d & G_c \\ G_c & G_d \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} + \begin{bmatrix} G_{F_b} & G_{F_p} \\ G_{F_b} & G_{F_p} \end{bmatrix} \begin{bmatrix} F_b \\ F_p \end{bmatrix}$$

$$G_d = k_I \left(\frac{D_{z\psi} + L^2 D_{zy}}{D_{zy} D_{z\psi}} \right) \qquad G_{F_p} = \frac{N_y}{D_{zy} D_{y_p}}$$

$$G_c = k_I \left(\frac{D_{z\psi} - L^2 D_{zy}}{D_{zy} D_{z\psi}} \right) \qquad G_{F_b} = \frac{1}{D_{zy}}$$

Guidance Control: Bogie MIMO system block diagram



$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \underbrace{\left[I + G_M G_{bI}\right]^{-1} G_M}_{G_{Iz}} \begin{bmatrix} I_{1s} \\ I_{2s} \end{bmatrix}$$

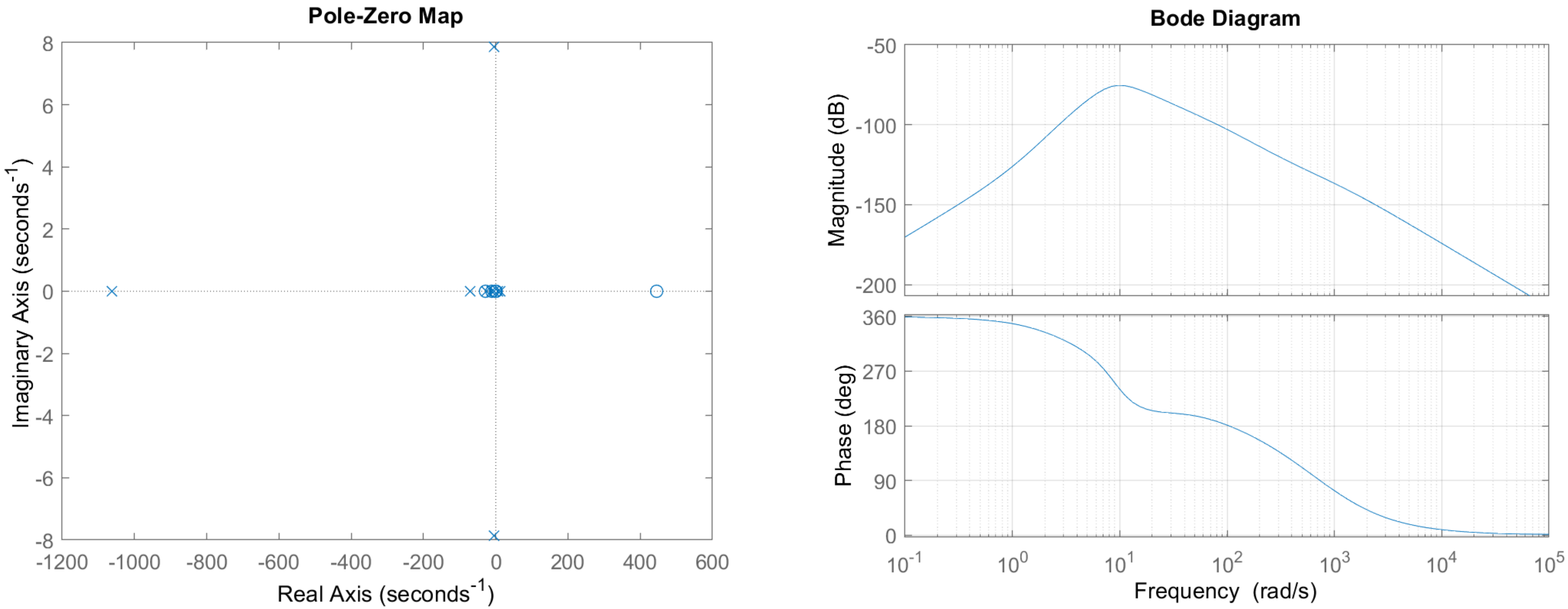
$$G_{Iz} = \left[I + G_M G_{bI}\right]^{-1} G_M = \frac{1}{(1+G_d G_b)^2 - G_c^2} \begin{bmatrix} 1 + G_d G_b & -G_c \\ -G_c & 1 + G_d G_b \end{bmatrix} \begin{bmatrix} G_d & G_c \\ G_c & G_d \end{bmatrix}$$

$$= \frac{1}{(1+G_d G_b)^2 - G_c^2} \begin{bmatrix} G_d + G_d^2 G_b - G_c^2 & G_c + G_d G_b G_c - G_c G_d \\ G_c + G_d G_b G_c - G_c G_d & G_d + G_d^2 G_b - G_c^2 \end{bmatrix}$$

Virgin hyperloop

Guidance Control: Preliminary Analysis

G_{Iz} off-diagonal Elements



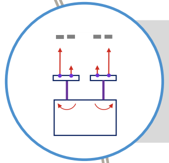
Guidance Control: Conclusions

- Non-minimum phase off diagonal elements cause limitations on the overall bandwidth of the closed loop system. It also induces more oscillations in the response as compared to the case with only diagonal elements.

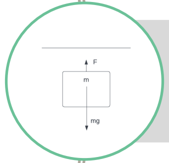
- It is possible tune the suspension parameters to make the off-diagonal elements at least marginally stable and have a low gain in the desired frequency range.

OVERVIEW

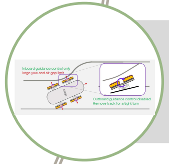
Goals



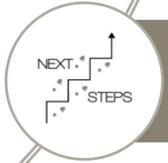
Supervisory Control for Levitation



Single EM engine control simulations



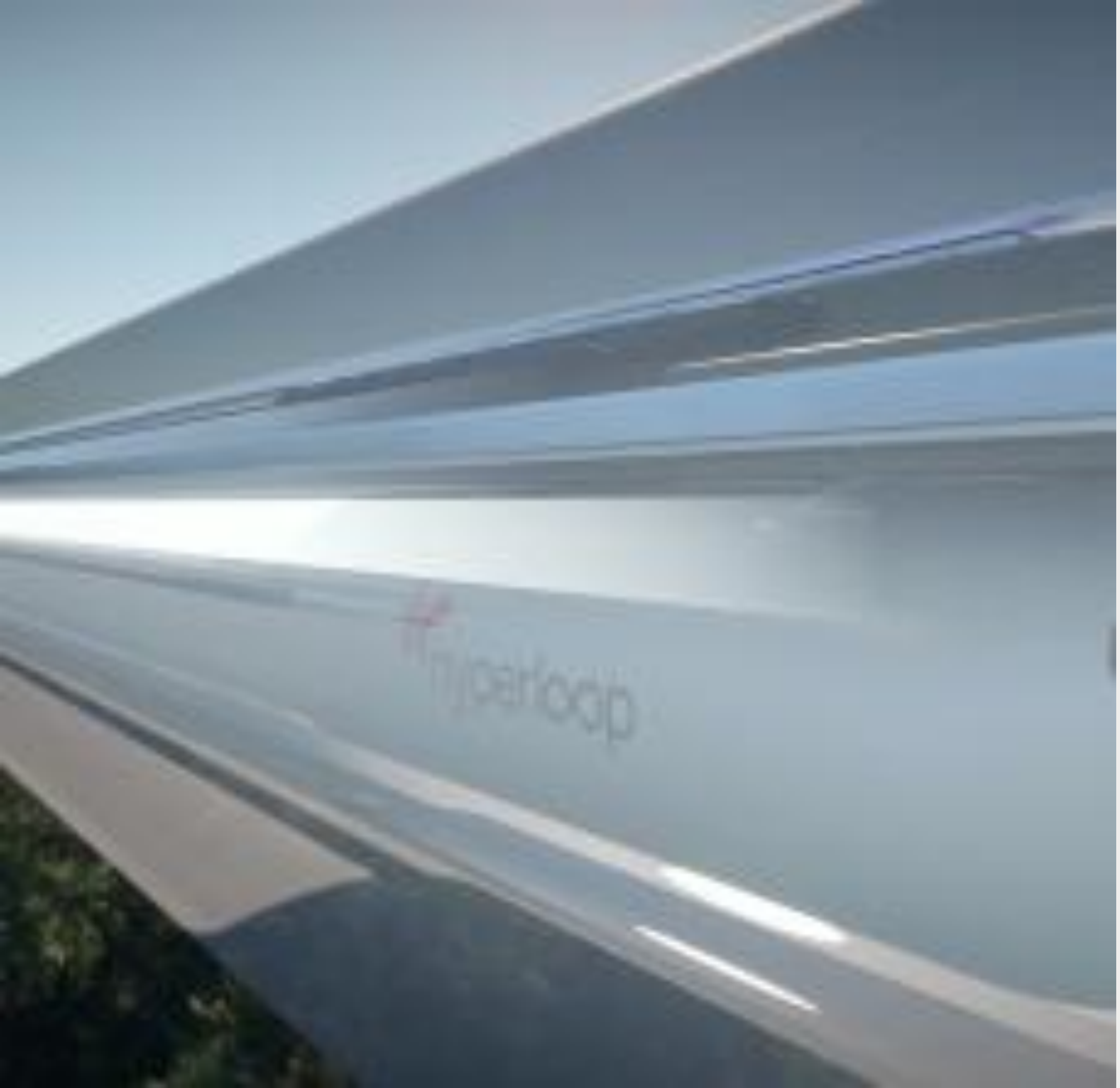
Guidance Control underdamping Investigation



Conclusion and Future Work

Next steps…

- Analysis of stability of the multi-rate (sampling frequencies) gap control system with the supervisor (10kHz Current Control, 1k Hz Gap Control and 100 Hz Supervisory Control).
- Control architecture for changing gap reference more than ± 5 mm (feedback linearization or gain scheduling methods for gap control).
- Possible requirements on suspension design for making the cross-coupling terms in the MIMO bogie model passively stable for a decoupled control design (Roth Stability analysis on the off-diagonal transfer functions can show the requirements on suspension parameters) .



Thank **you**!

Special thanks to:

- Dr. Kerry Sun
- Rebel Sequera
- Dr.Ruiyang Wang

APPENDIX

Guidance Control: Equations for stability analysis

$$G_{F_b} = \frac{1}{D_{zy}} = \frac{m_p s^2 + N_y}{m_p m_b s^4 + N_y s^2(m_p + m_b - 2k_z m_p) - 2k_z N_y}$$

$$G_{F_p} = \frac{N_y}{D_{zy} D_{y_p}} = \frac{N_y}{m_p m_b s^4 + N_y s^2(m_p + m_b - 2k_z m_p) - 2k_z N_y}$$

$$G_d = k_I \left(\frac{D_{z\psi} + L^2 D_{zy}}{D_{zy} D_{z\psi}} \right) = k_I \left(\frac{D_{y_p} N_{z\psi} + L^2 D_{\psi_p} N_{zy}}{N_{zy} N_{z\psi}} \right)$$

$$G_c = k_I \left(\frac{D_{z\psi} - L^2 D_{zy}}{D_{zy} D_{z\psi}} \right) = k_I \left(\frac{D_{y_p} N_{z\psi} - L^2 D_{\psi_p} N_{zy}}{N_{zy} N_{z\psi}} \right)$$

$$\begin{aligned}
N_y &= b_y s + k_y \\
N_\psi &= b_\psi s + k_\psi \\
D_{y_b} &= m_b s^2 + b_y s + k_y = m_b s^2 + N_y \\
D_{\psi_b} &= J_b s^2 + b_\psi s + k_\psi = J_b s^2 + N_\psi \\
D_{y_p} &= m_p s^2 + b_y s + k_y = m_p s^2 + N_y \\
D_{\psi_p} &= J_p s^2 + b_\psi s + k_\psi = J_p s^2 + N_\psi \\
D_y &= \frac{D_{y_b} D_{y_p} - N_y^2}{D_{y_p}} = \frac{m_p m_b s^4 + N_y s^2(m_p + m_b)}{m_p s^2 + N_y} \\
D_\psi &= \frac{D_{\psi_b} D_{\psi_p} - N_\psi^2}{D_{\psi_p}} = \frac{J_p J_b s^4 + N_\psi s^2(J_p + J_b)}{J_p s^2 + N_\psi} \\
D_{zy} &= D_y - 2k_z = \frac{m_p m_b s^4 + N_y s^2(m_p + m_b - 2k_z m_p) - 2k_z N_y}{m_p s^2 + N_y} \\
D_{z\psi} &= D_\psi - 2L^2 k_z = \frac{J_p J_b s^4 + N_\psi s^2(J_p + J_b - 2L^2 k_z J_p) - 2L^2 k_z N_\psi}{J_p s^2 + N_\psi}
\end{aligned}$$

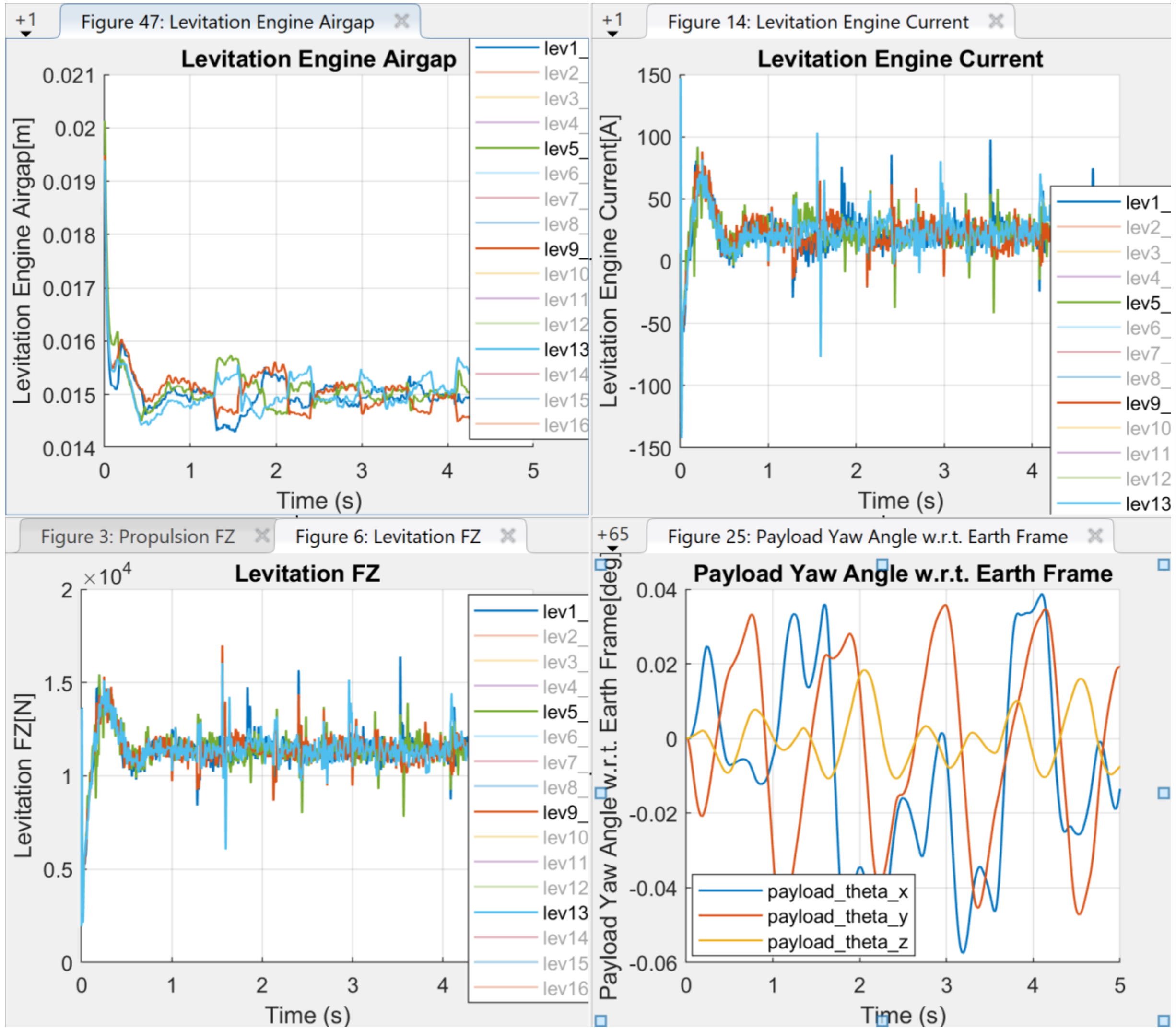
The roots of the following polynomials determine the stability of the off-diagonal elements:

$$N_{z\psi} = J_p J_b s^4 + b_\psi(m_p + m_b - 2L^2 k_z J_p)s^3 + k_\psi(J_p + J_b - 2L^2 k_z J_p)s^2 - 2L^2 k_z b_\psi s - 2L^2 k_z k_\psi$$

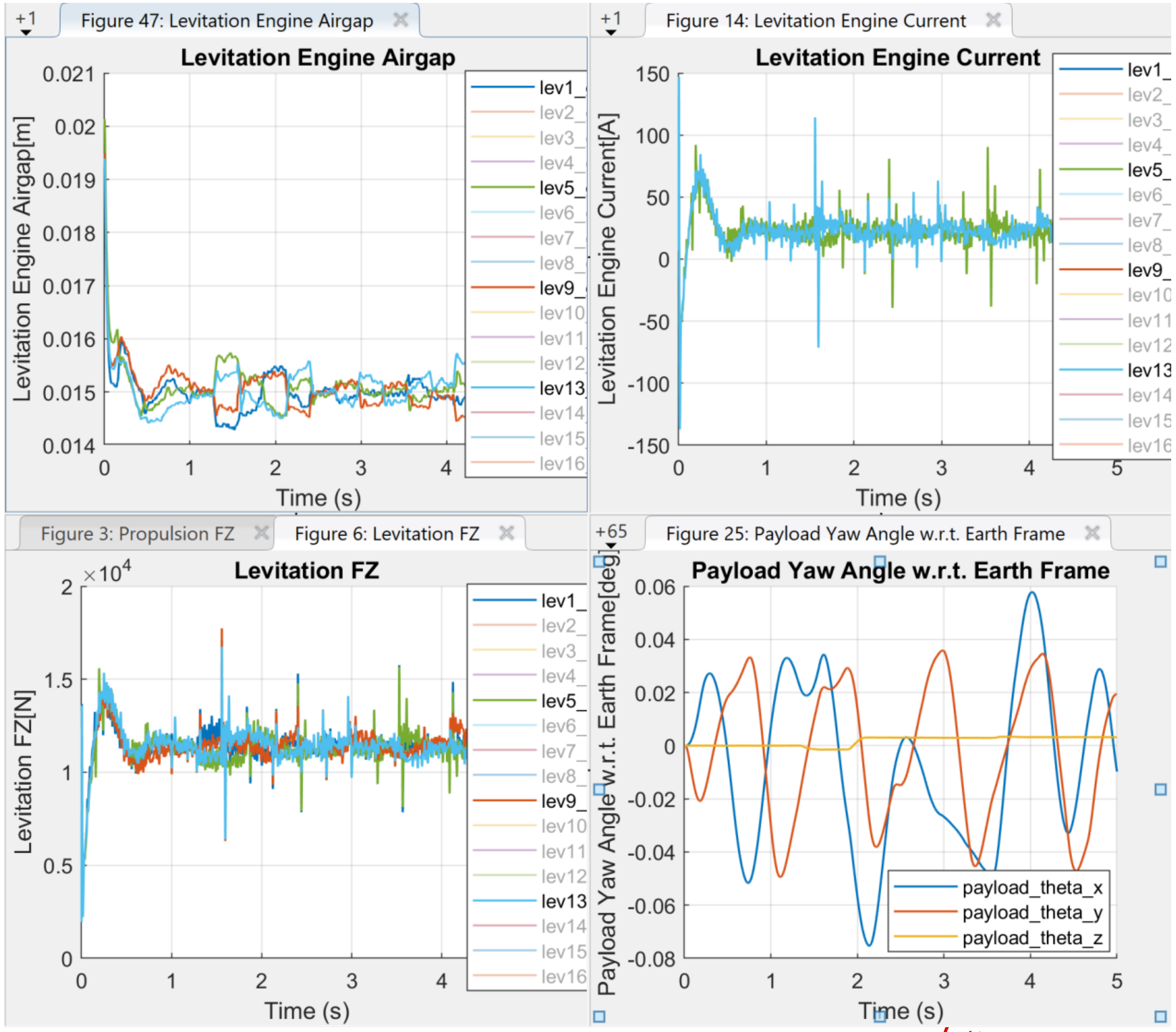
$$N_{zy} = m_p m_b s^4 + b_y(m_p + m_b - 2k_z m_p)s^3 + k_y(m_p + m_b - 2k_z m_p)s^2 - 2k_z b_y s - 2k_z k_y$$

Supervisor and PCC results*

Supervisory Control



Partially Centralized Control



*Collaboration with Dr.Ruiyang Wang

Virgin hyperloop