

# The Feasibility of Motion Tracking Camera System In Magnetic Suspension Wind Tunnel Tests

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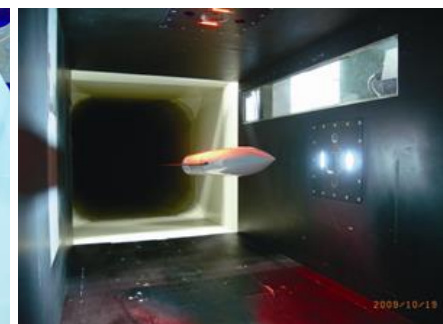
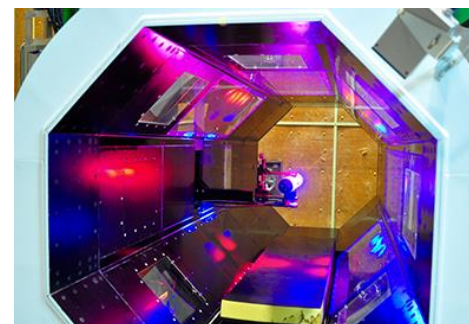
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# Background

- Past Magnetic Suspension Balance System (MSBS) developments at supersonic speeds include RAE Farnborough, MIT, Tohoku
- Magnetic Suspension Balance System (MSBS) designed and constructed by MIT
- Operated at NASA in 1990
- Recommissioned by ODU with new motor and drive
- Returned to NASA 2016
- New power amplifiers and control system



[Magnetic Suspension In Hypersonic Wind Tunnel - Farnborough \(1966\)](#)



[Left: Tohoku University. Right: JAXA](#)



[ODU Subsonic Wind tunnel – NASA Langley Research Center](#)

# Introduction and Objectives

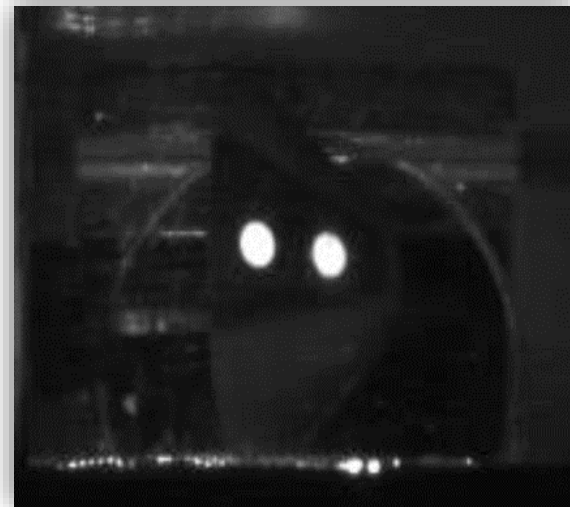
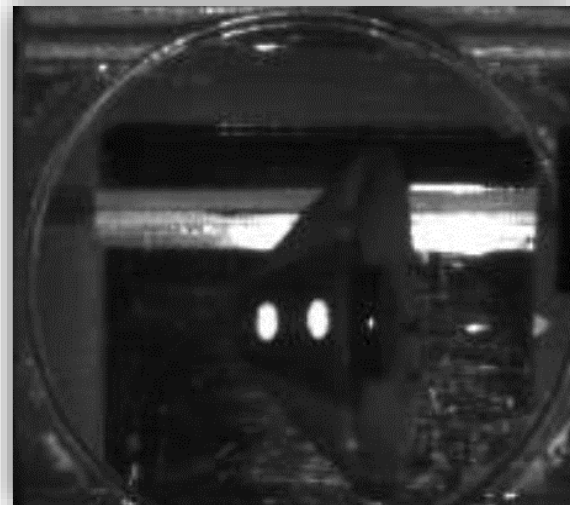
- Dynamic stability measurements of ‘stingless’ atmospheric entry capsules in support of the Entry Systems Modeling program at NASA
- Enhance system capability from three to five degrees of freedom (DOF) control with camera system.
- Current operations falls between the capabilities of onsite testing facility : vertical spin tunnel and transonic dynamic tunnel (TDT)
- The effort demonstrates technology suitability for implementation in future supersonic tunnel. *“The road to high  $Q_s$ ”*

Hybrid MSBS system: 3-DOF to 5-DOF

Degrees of Freedom (DOF)						
Measuring Unit	$x$	$y$	$z$	$\theta$	$\psi$	$\phi$
EPS	✓	✓	✓			
Camera System	✓		✓	✓		✓



Examples of tested entry capsules



Two camera views of a levitating model

# Outline

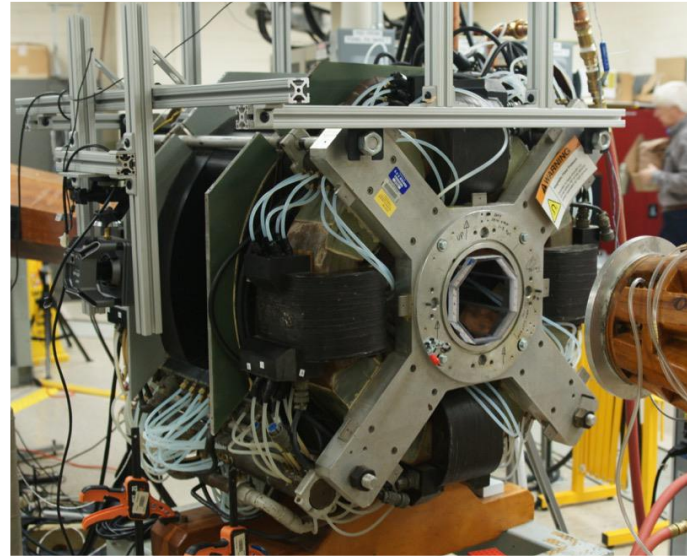
- Background
- Introduction and Objectives
- Test Facility
- System Overview
- Controller
- Camera System
- Tracking Results
- Data Reduction Process
- Conclusion
- Future Work

# Test Facility



ODU subsonic wind tunnel at NASA Langley

- **Speed range: 5 to +60 m/s**
- **Dynamic pressure: +2 kPa**
- **Turbulent intensity: 0.1 – 0.25%**



Magnetics Suspension Balance System (MSBS)

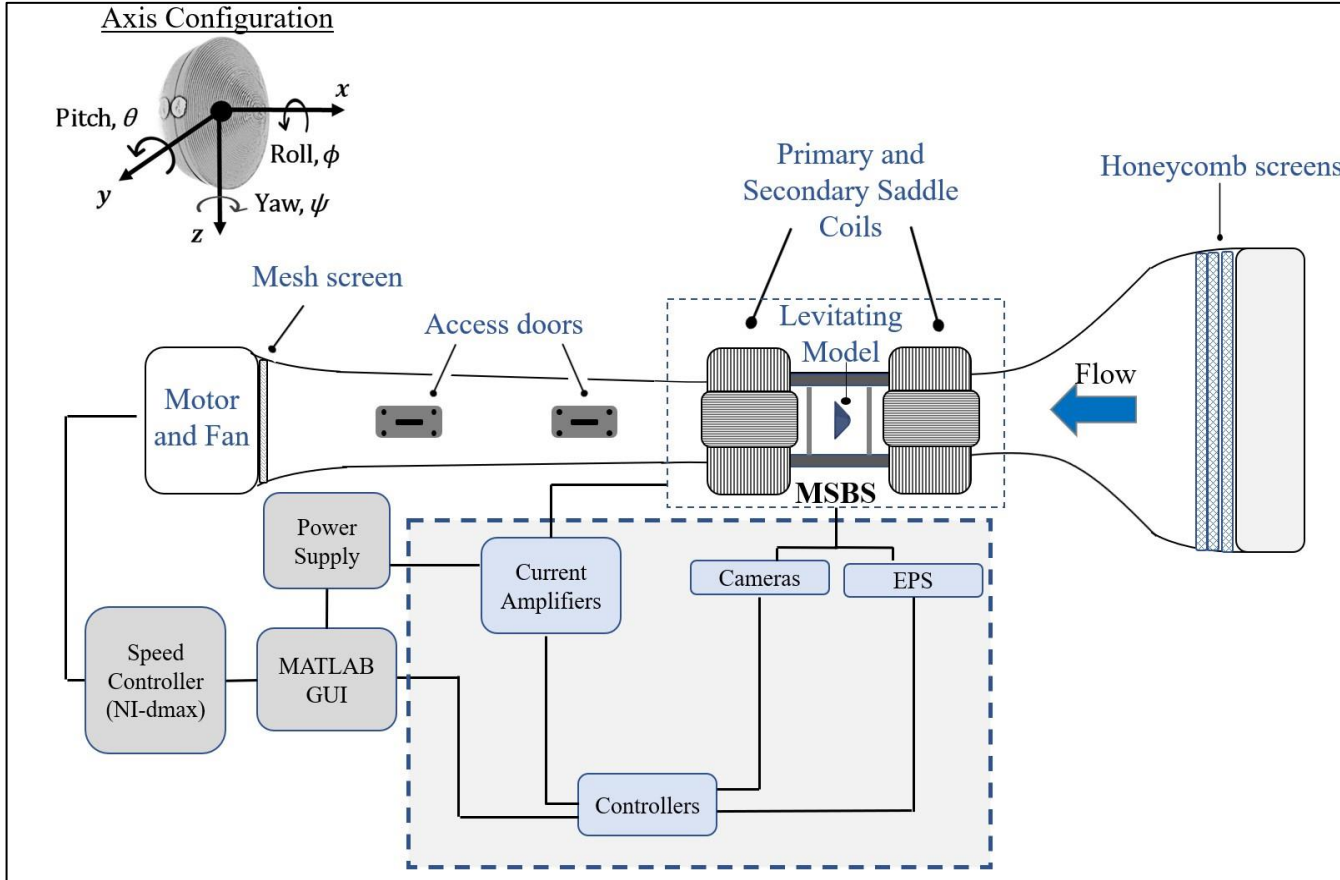
- **Magnetizing primary and secondary saddle coils**
- **Transverse magnetization**



Electromagnetic position sensor (EPS) cage

- **EPS cage**
- **Fitted magnets and copper coils**

# System Overview



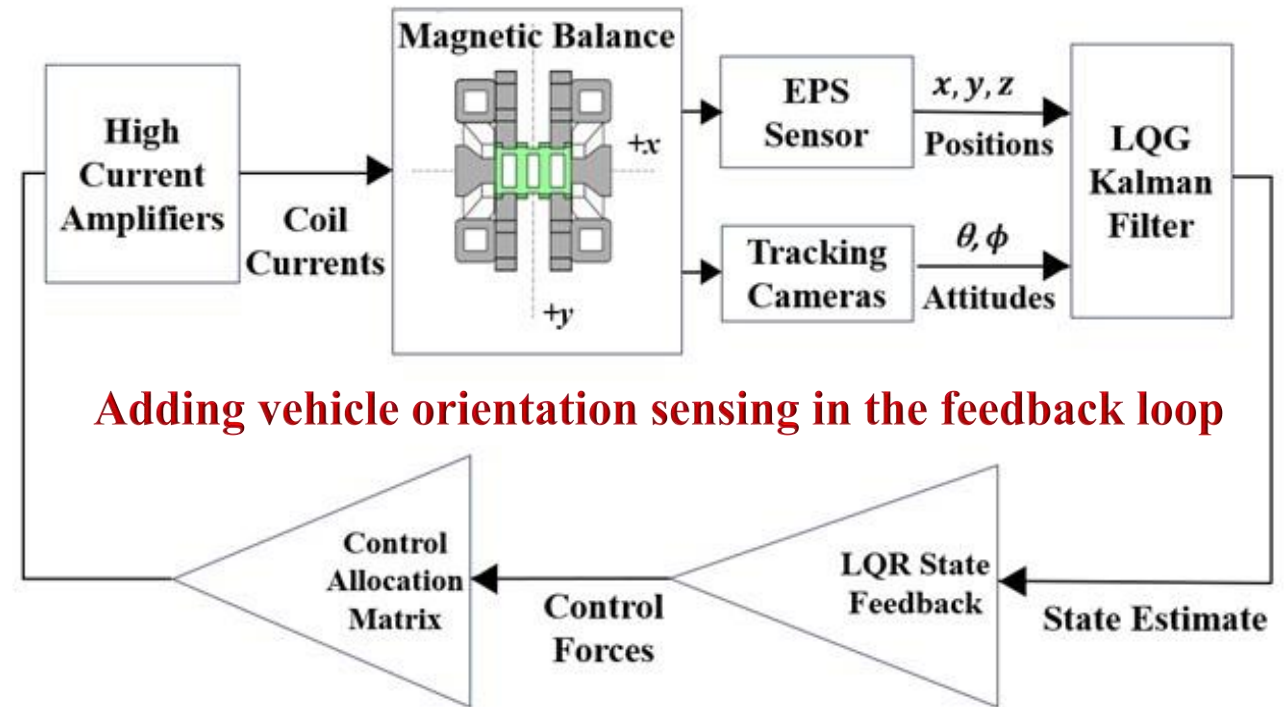
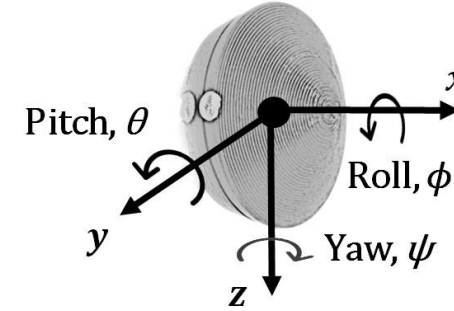
Schematic of the operating system

## Key hardware and system components

Component	Specification
Tunnel's test section	6.25 inches wide/Octagonal
Operating speed range	5 m/s to 60 m/s
Mach number range	0.2 to 0.5
Reynolds number range (Diameter based)	$1.5 \times 10^4$ to $2 \times 10^5$
Tunnel's turbulent intensity	0.1% to 0.25%
Motion Tracking camera	Two PrimeX22 OptiTrack
Camera nominal frame rate	360 Hz
Camera resolution (nominal)	$2048 \times 1088$ Pixels
Camera/EPS capture rates	500 Hz
Light source	LED Infrared
Lens, $f\#$ , filter	6.8 mm, $f/1.6$ , 850 nm bandpass
Field of views (Horizontal $\times$ Vertical)	$79^\circ \times 47^\circ$ at 360 Hz, $79^\circ \times 18^\circ$ at 1000 Hz
Tracking pixel accuracy	0.15 mm
Software and API	Motive 3.1 and C++
Retroreflective markers	3M-7610

# Controller

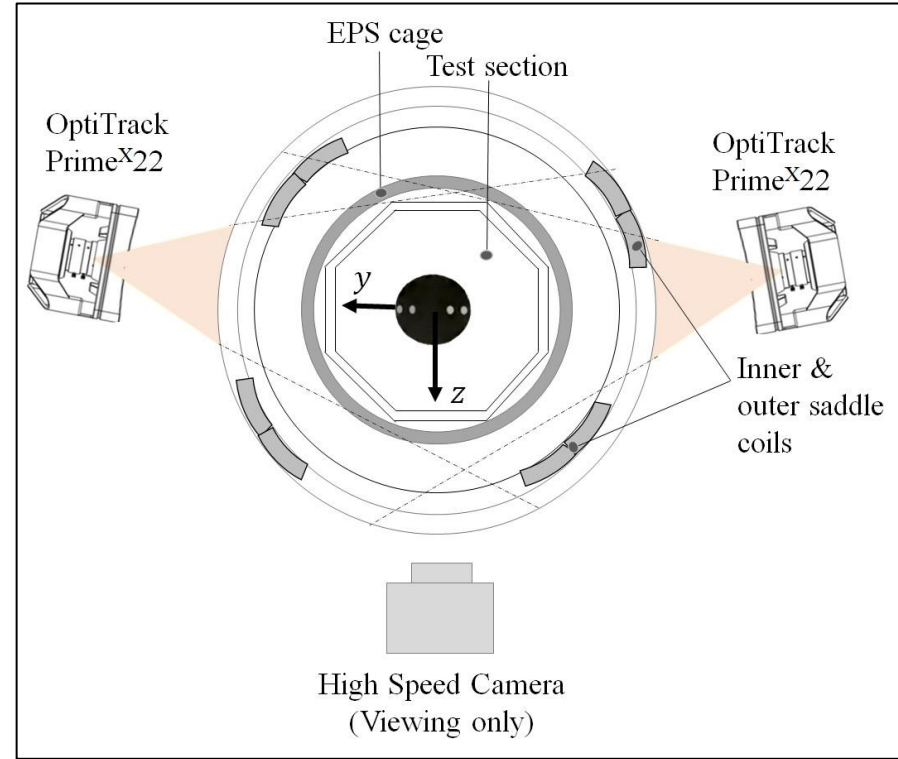
- EPS and Camera measurements
- Linear Quadratic Gaussian (LQG)
- Linear Quadratic Regulator for state feedback
- Allocate control inputs to current sensors/amplifiers
- Current sent to magnetic coil to manipulate magnetic field/flux for levitation



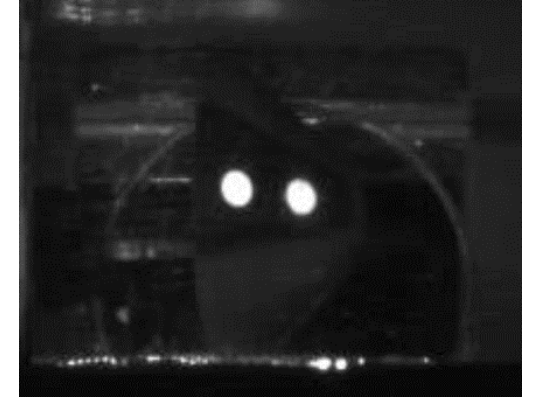
# Camera System



Camera view with respect to model and test section

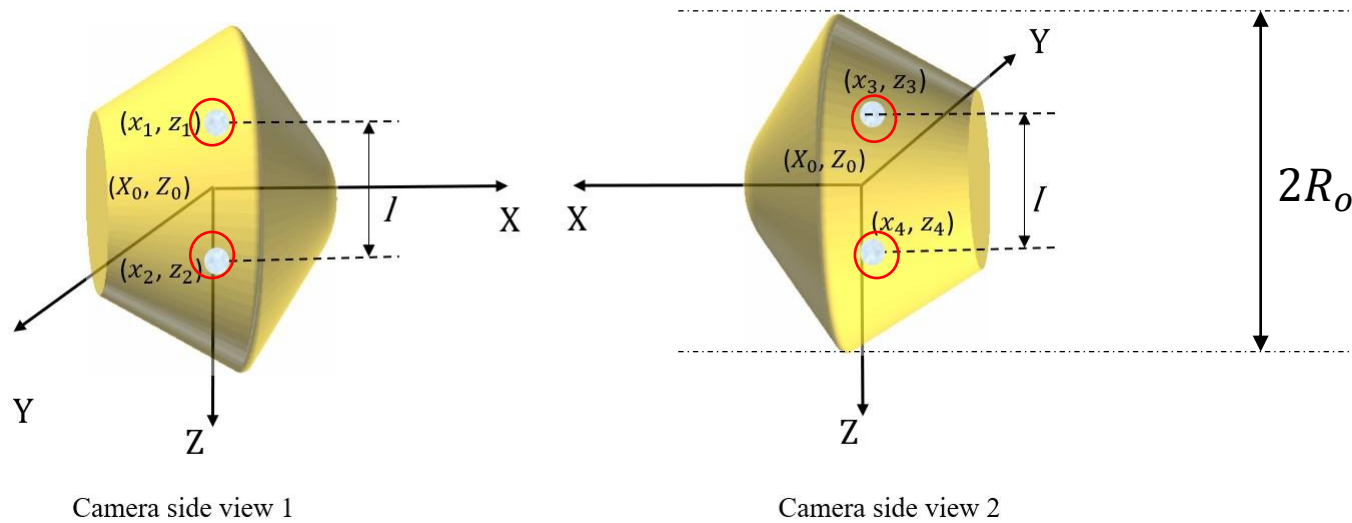


Tracking and viewing cameras used



Retroreflective markers for tracking and rigid body identification

# Camera Tracking Algorithm



## Minimum distance criteria

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (z_i - z_j)^2}$$

## Averaging and attitude estimates

$$X_o = \frac{1}{4} \sum_{i=1}^4 x_i$$

$$Z_o = \frac{1}{4} \sum_{i=1}^4 z_i$$

$$\phi = \frac{1}{2} \left( \frac{z_1 - z_3}{2R_o} + \frac{z_2 - z_4}{2R_o} \right)$$

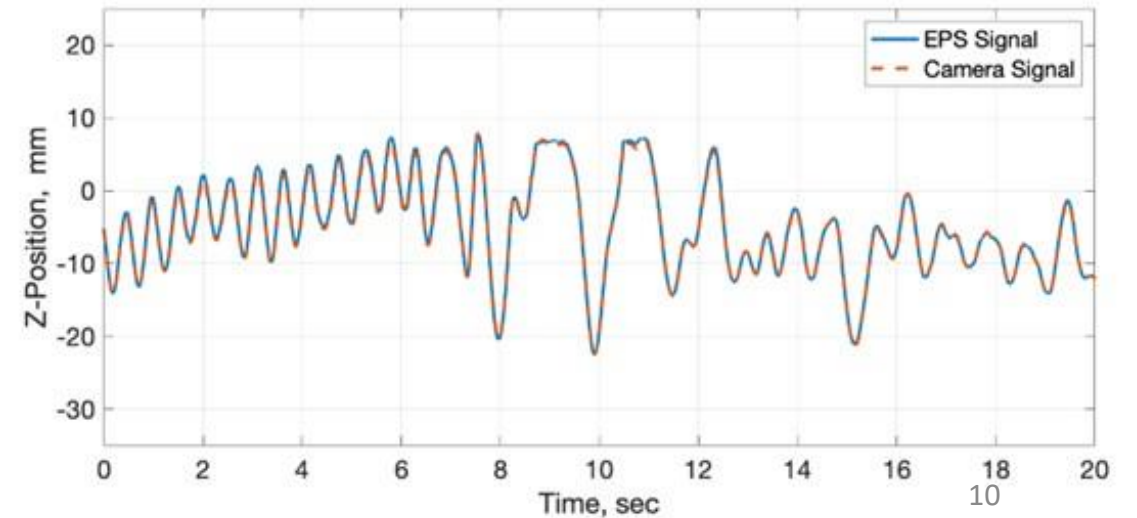
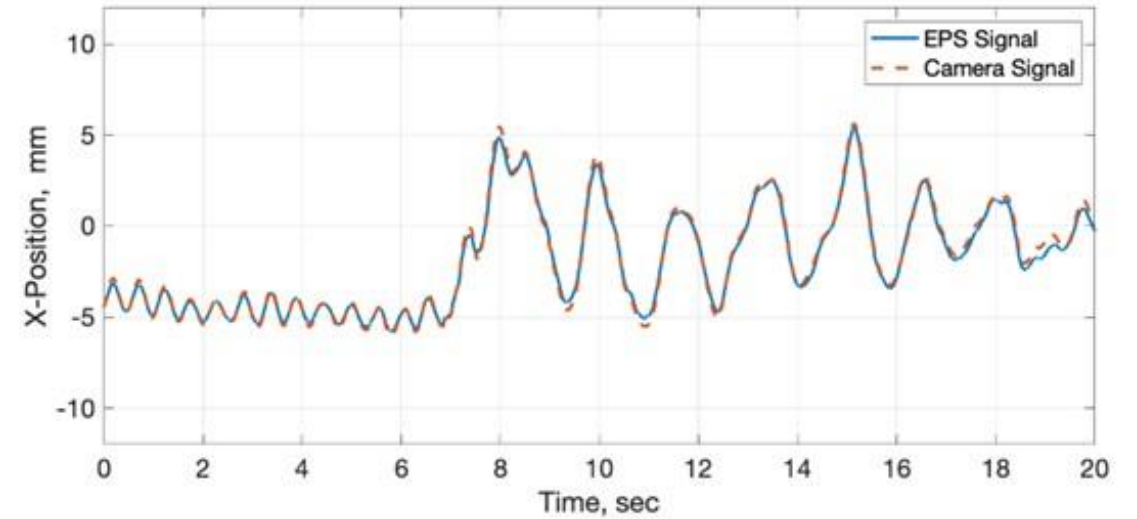
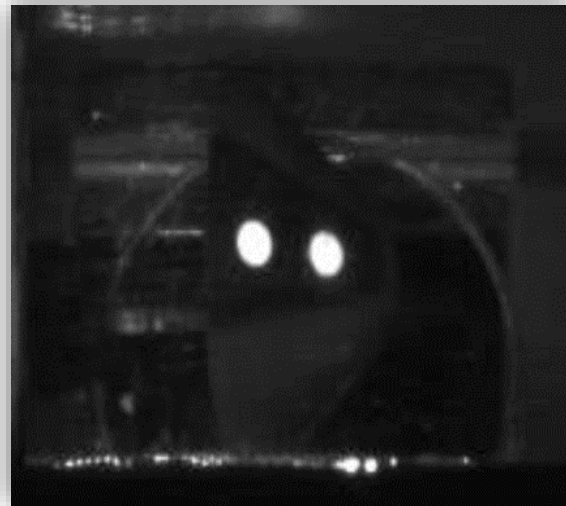
$$\theta = \frac{1}{2} \left( \frac{x_2 - x_1}{l} + \frac{x_4 - x_3}{l} \right)$$

## Tracking Algorithm:

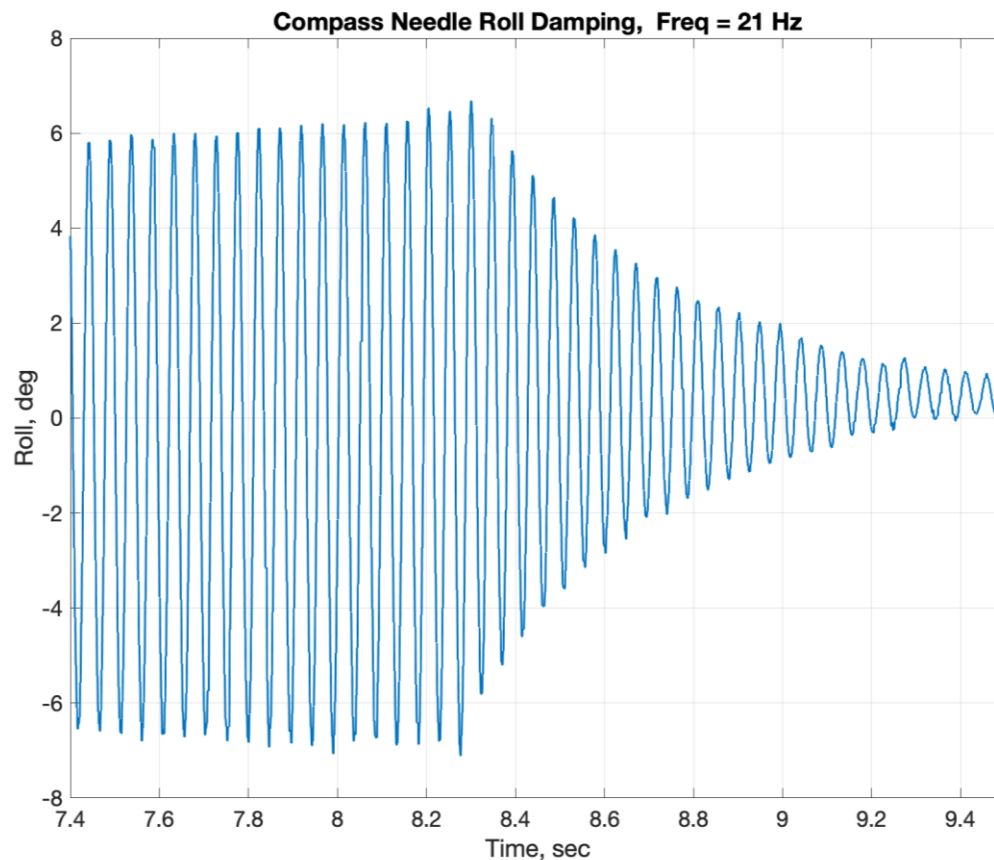
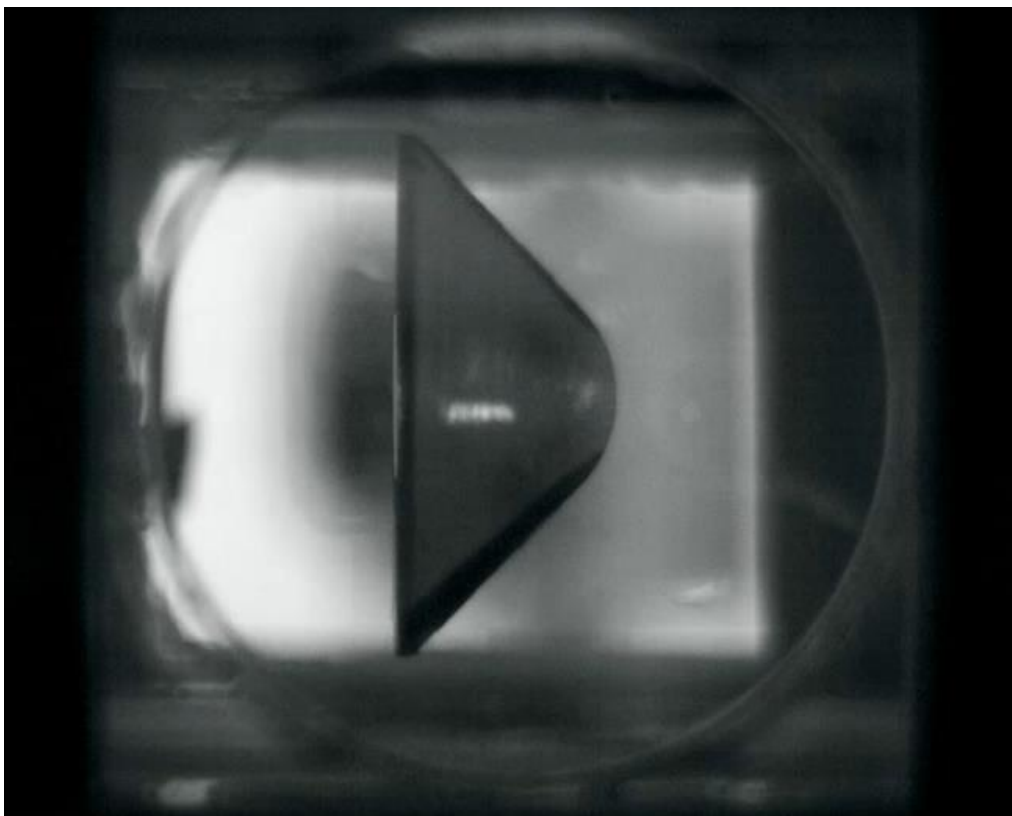
1. Identify marker's 2-D centroid via software's Application Programming Interface (API)
2. Use speedgoat code to calculate distance between all targets.
3. Apply minimum distance criteria. Sort X and Z positions and append data
4. Compute real-time pitch and roll measurements

# Tracking results (Flow off)

- Validation with existing EPS data
- Confidence in real-time pitch and roll measurements



# Roll control and damping with camera feedback

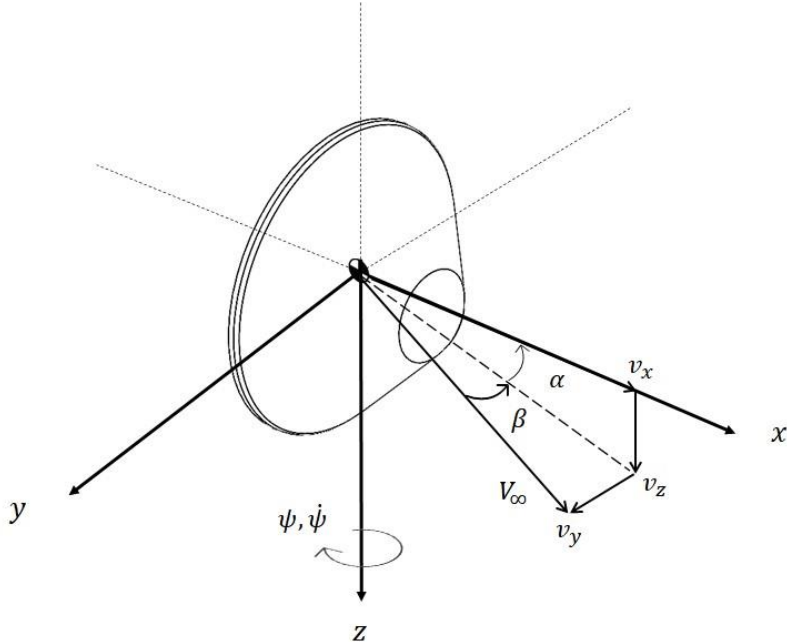


**Camera tracking algorithm provides real-time roll and pitch information for control**

Optical sensing for rotational control in the MSBS

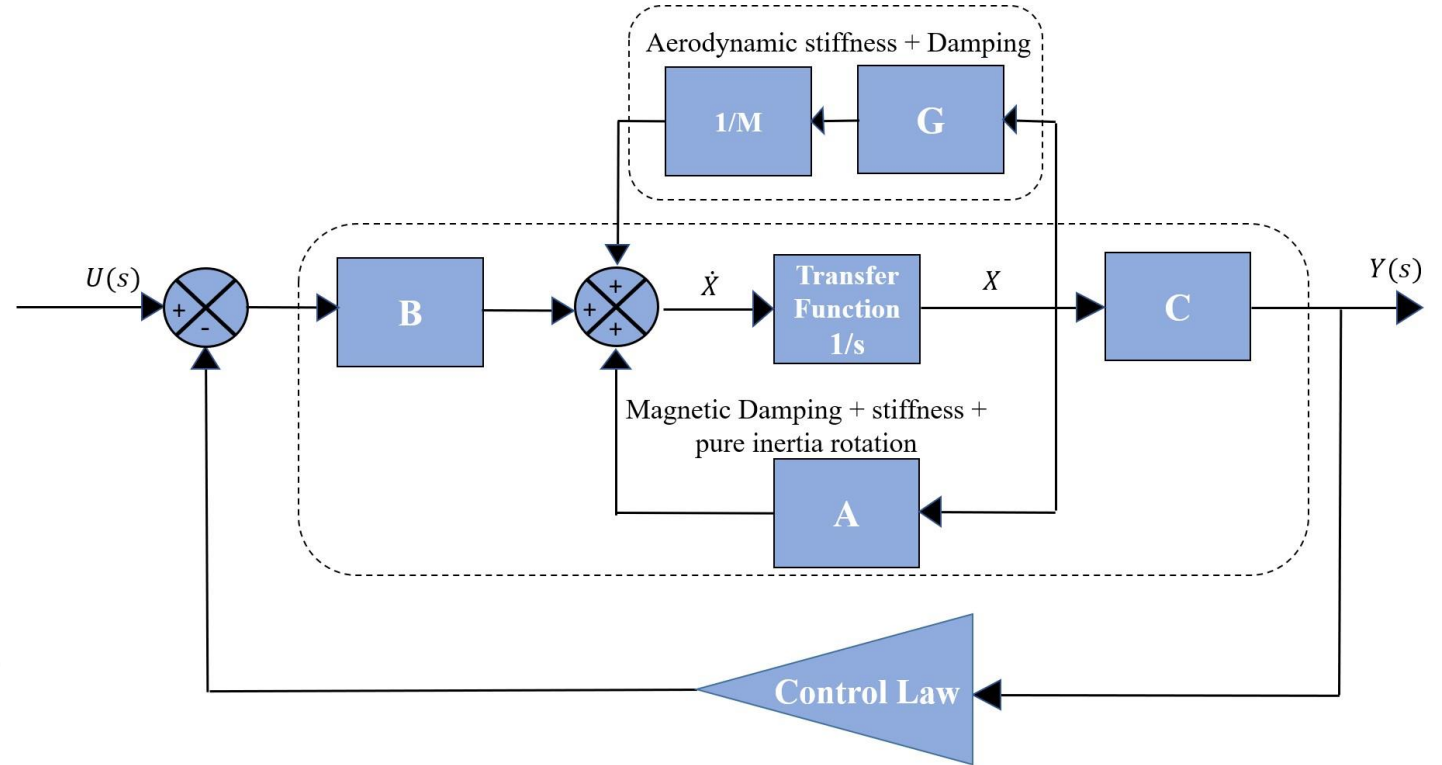
This can suppress the high frequency “compass needle” chatter seen with some high-speed runs.

# Data reduction process



Decoupling of magnetic and aerodynamic forces to predict accurate dynamic characteristics

Analytical approach includes running the system identification in zero flow first to obtain magnetic forces contribution to capsule's oscillation growth/decay.



Block diagram representation of the two-way system identification used to isolate magnetic forces from aerodynamic forces

# Data reduction process

Identify magnet control and rotational inertial response without aerodynamic flow

$$\begin{bmatrix} \ddot{\psi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \psi \end{bmatrix} + \begin{bmatrix} 1/I_z \\ 0 \end{bmatrix} T$$

## Extracted parameters

$C_{n,r}$ : Yaw moment slope w.r.t. sideslip rate

$C_{L,\beta}$ : Lift curve slope

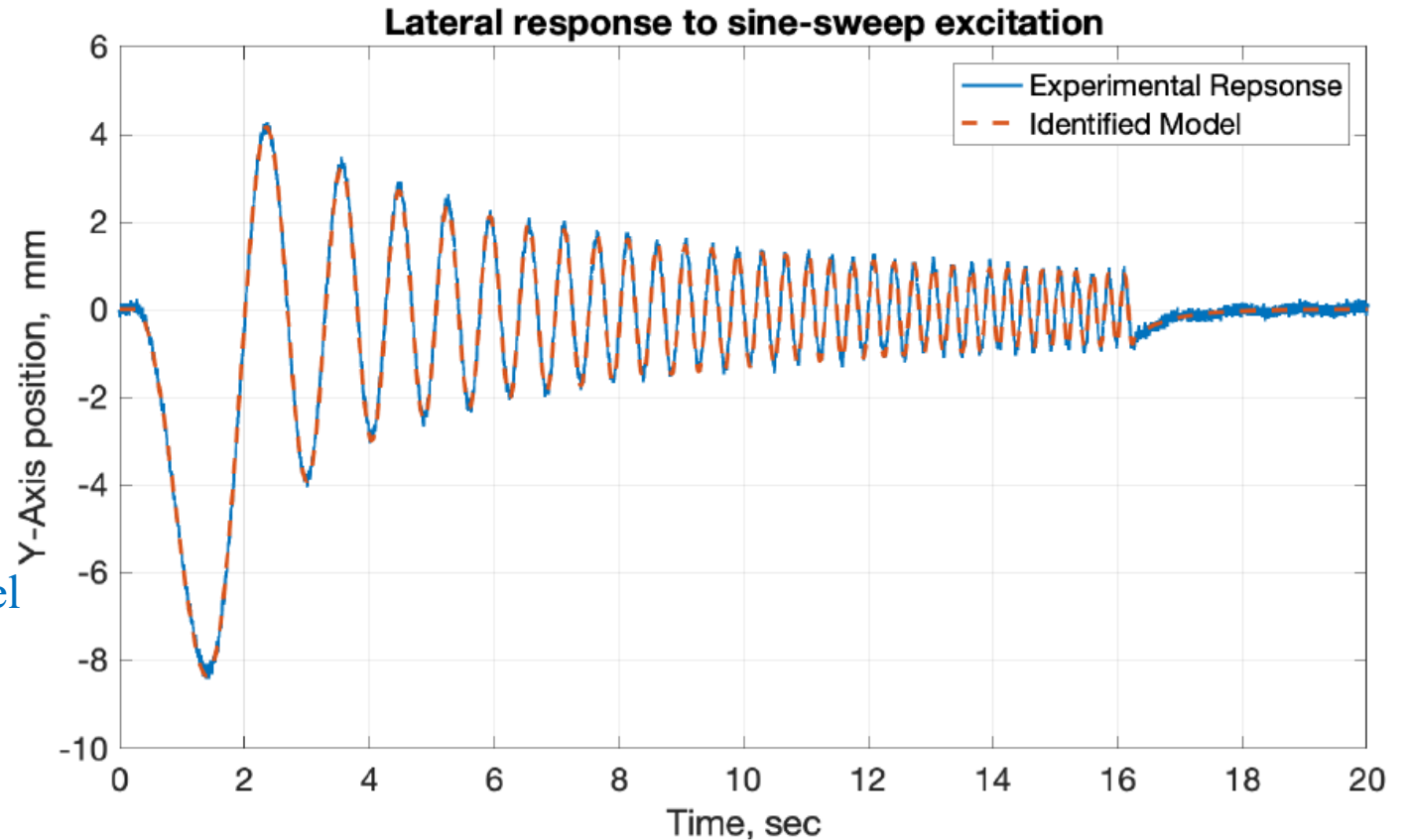
$C_{n,\beta}$ : Yaw moment slope w.r.t sideslip

To solve for these terms the previously identified model was used in a feedback loop with the aerodynamic model. “The greybox estimation problem”

$$F = \frac{1}{2} \rho V_\infty^2 S (C_{L,\beta} (-\psi + \dot{y}/V_\infty))$$

$$M = \frac{1}{2} \rho V_\infty^2 S \bar{C} (C_{n,\beta} (-\psi + \dot{y}/V_\infty + \frac{\bar{C}}{2V_\infty} C_{n,r} \dot{\psi}))$$

External disturbance applied. A chirp function applied with a small force and frequency sweep



Fourth order transfer function estimate for the closed-loop translational dynamics

# Summary

- Installed new camera system to existing magnetic suspension balance system
- Enhance system's control and feedback from 3 DoF EPS to 5 DoF EPS/Camera system
- Develop data reduction techniques to quantify vehicle aerodynamic characteristics
- **Incorporate camera tracking into closed feedback control system in pitch and roll to control levitating entry capsules at high flow speeds.**

# Acknowledgments

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