Hyperloop | Control System

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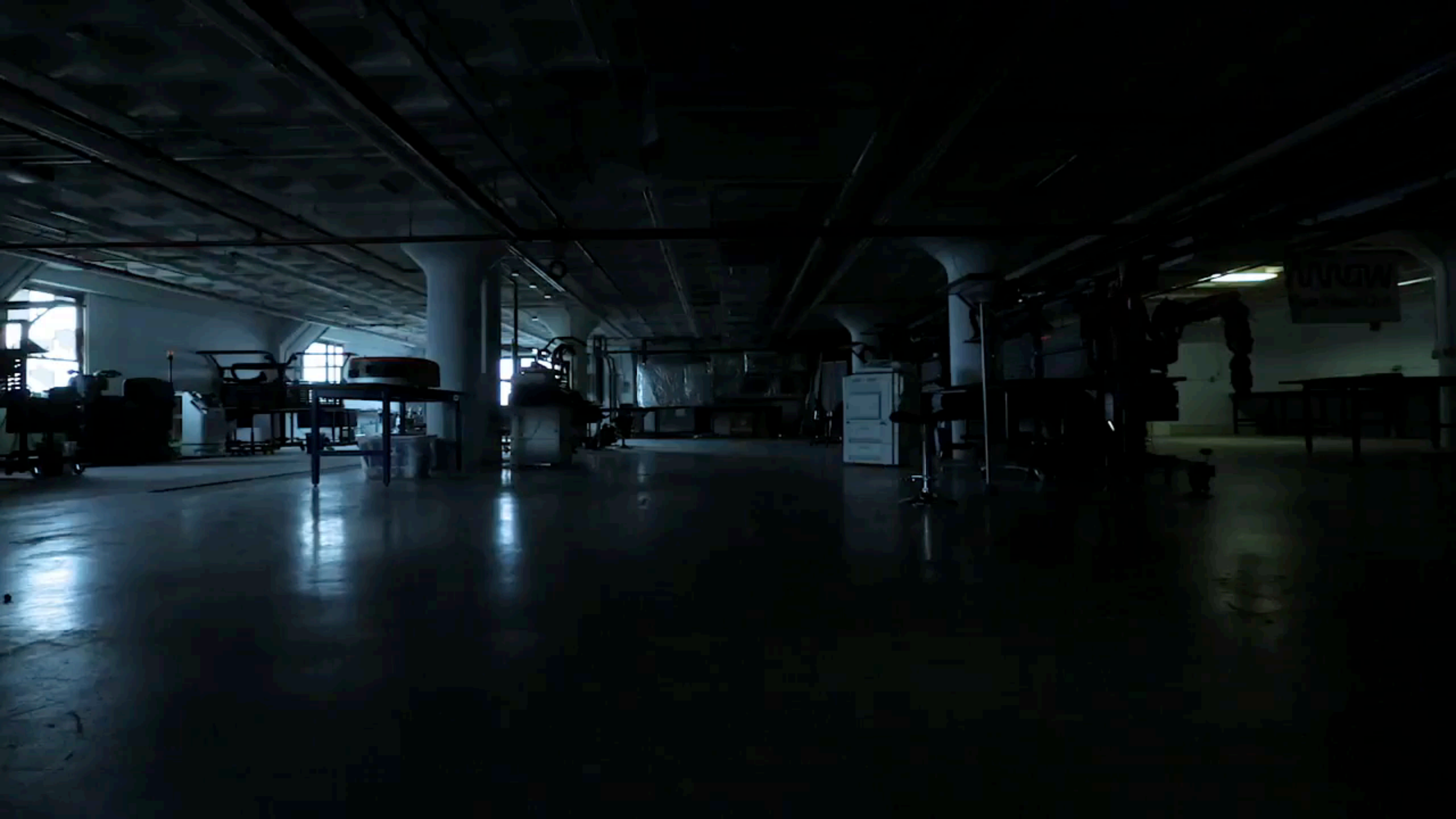
Background | Hyperloop

- **Transportation**
  - Pods
  - Low pressure tubes
  - High speed
- **Under Development**
  - Hyperloop One
  - Boring Company
  - Northeastern University
- **Engineering Challenges**
  - Propulsion
  - Safety
  - Air skates

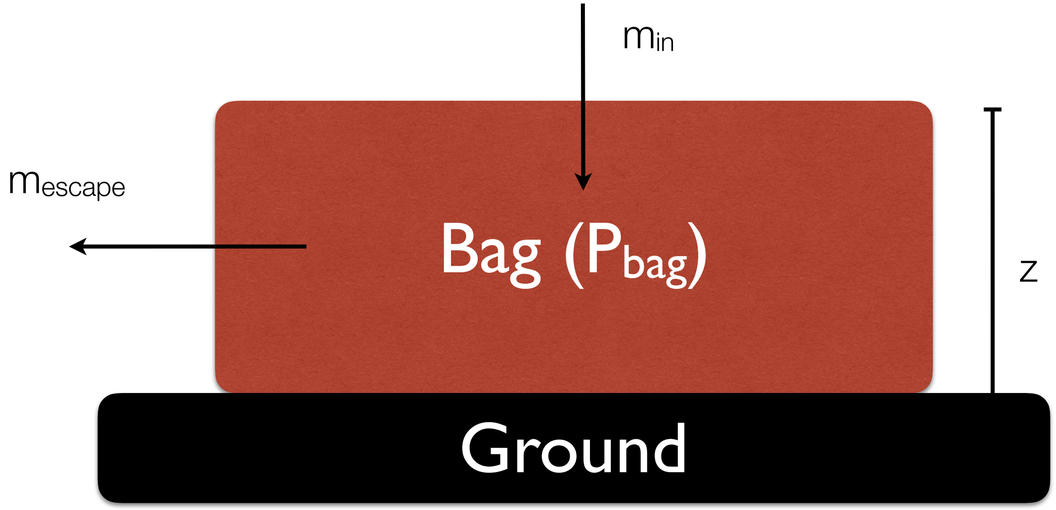


HLCS | Problem Formulation

- **Problem Statement**
  - **Levitation at high speed must be stable**
  - **Must have control over all pod actuators and sensors**
- **Problem Details**
  - **Paradigm will test pod at 600mph in Summer 2018**
    - Levitation must be stable to avoid damaging levitation mechanism
    - Avionics must actively control levitation and report pod state
- **Solution Requirements**
  - **Reliable model of pod dynamics**
    - Validated against real pod
  - **Avionics infrastructure to support active pod control**

Stability | Model of Hyperloop Pod

- **Vertical approximate dynamics of air skates**
- **Based on hovercrafts**
- **Stiff, nonlinear model**
  - **Gas compression**
  - **Non-darcy flow**



$$M\ddot{z} = (P_{bag} - P_{atmo})A - Mg$$

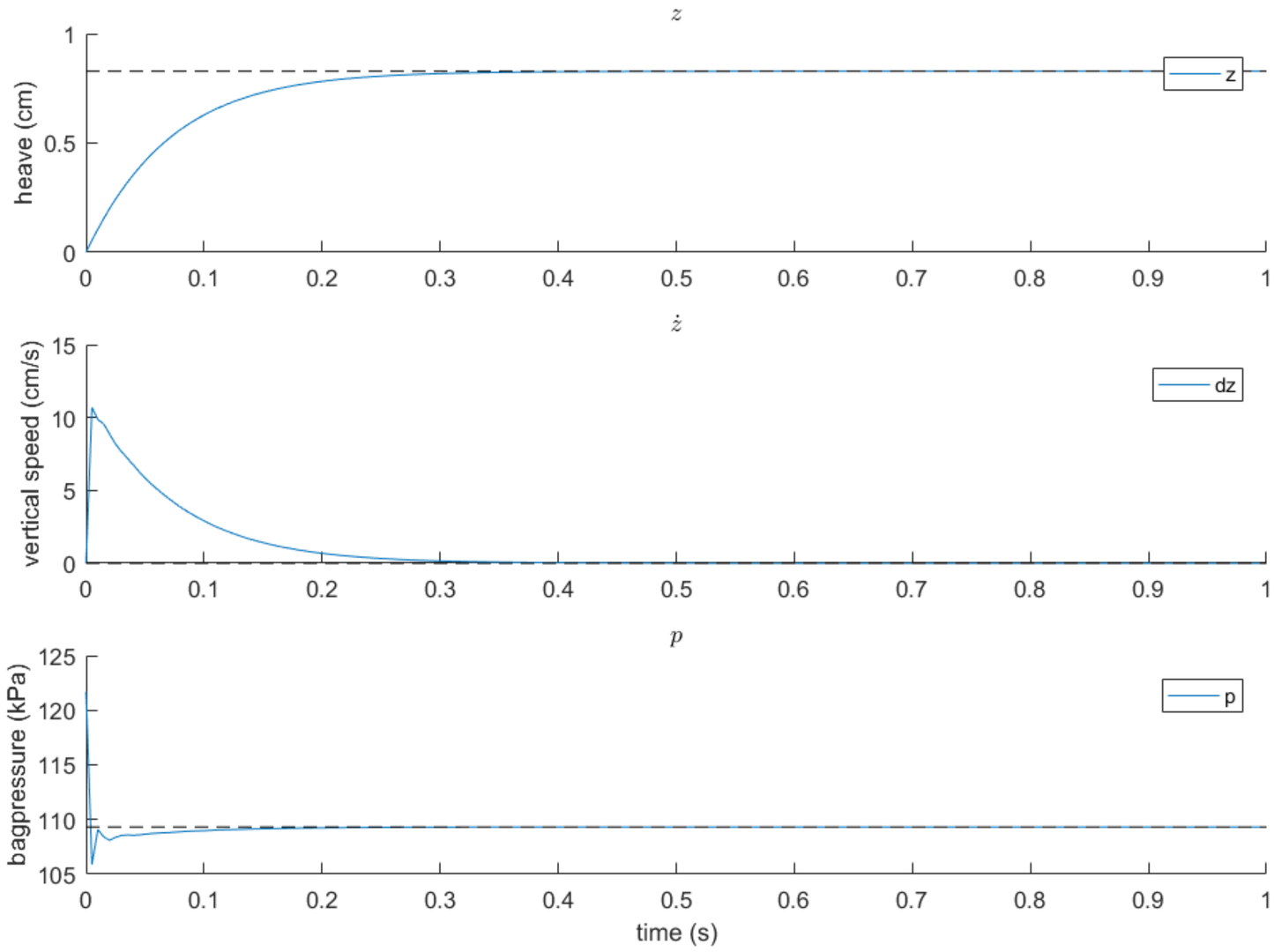
$$\dot{P}_{bag} = \frac{\gamma RT}{Az}(\dot{m}_{in} - \dot{m}_{escape} - \frac{P_{bag}A\dot{z}}{RT})$$

$$\rho_{atmo}\frac{\partial P}{\partial x} = \beta(\frac{\dot{m}_{escape}}{A_e})^2 + \mu(\frac{\dot{m}_{escape}}{A_e})$$

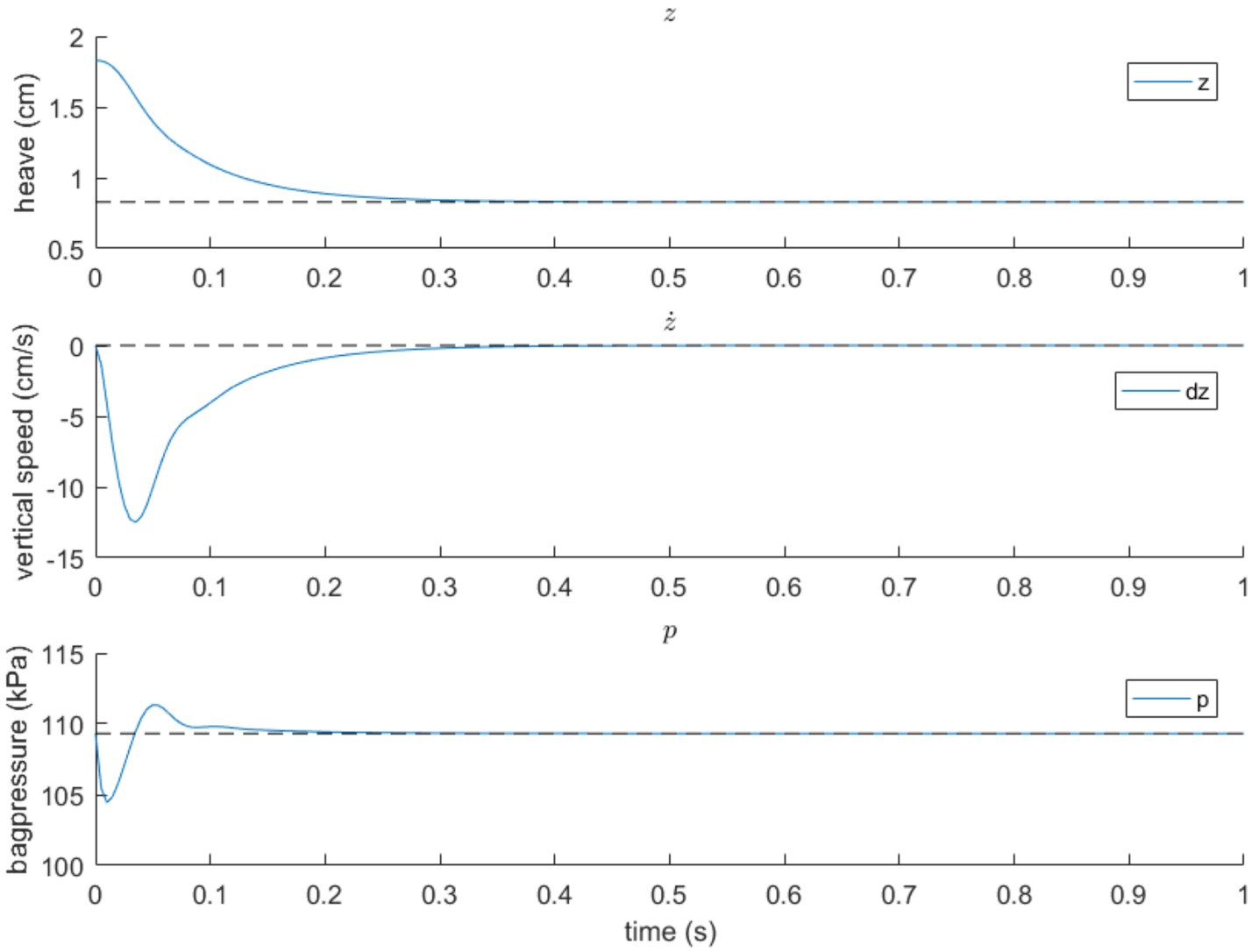
$$A_e = Per * z$$

$$\frac{\partial P}{\partial x} = \frac{P_{bag} - P_{atmo}}{\ell}$$

Stability | **Plots of Motion:** Pod liftoff

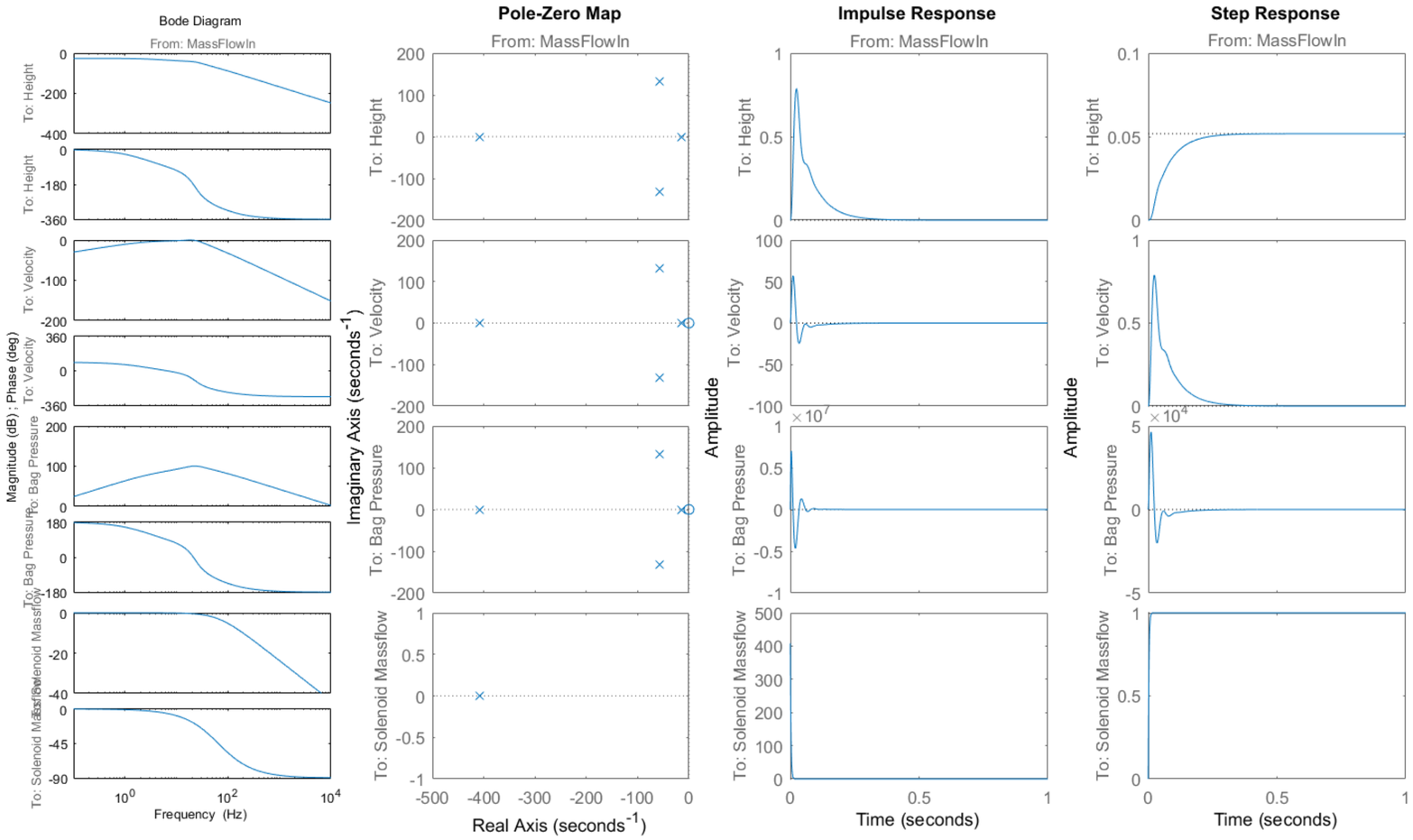


Stability | **Plots of Motion:** Pod drop (1cm)



Stability | Linearization

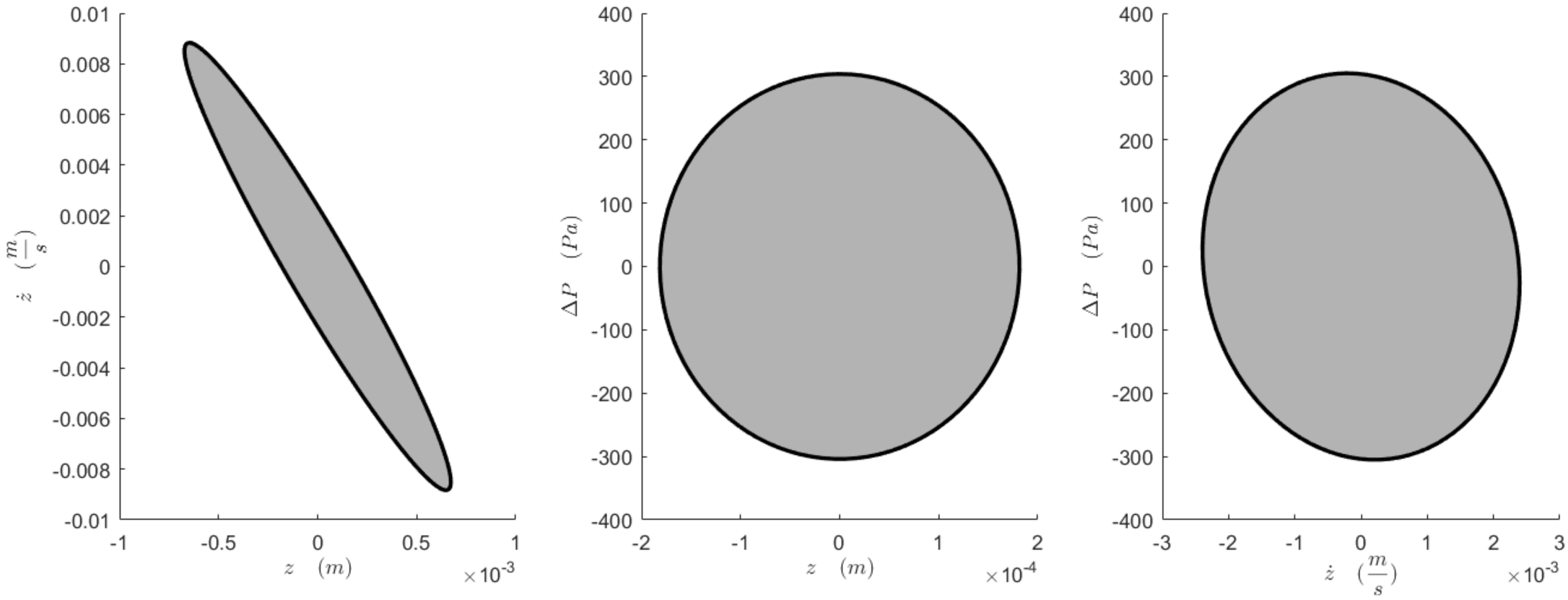
- **Poles of system:**
  - **Mass flow lowpass (-408)**
  - **Non-darcy flow (-14.8)**
  - **Heave motion (-57.9±133j)**
- **System is open loop stable**



Stability | Model Validation

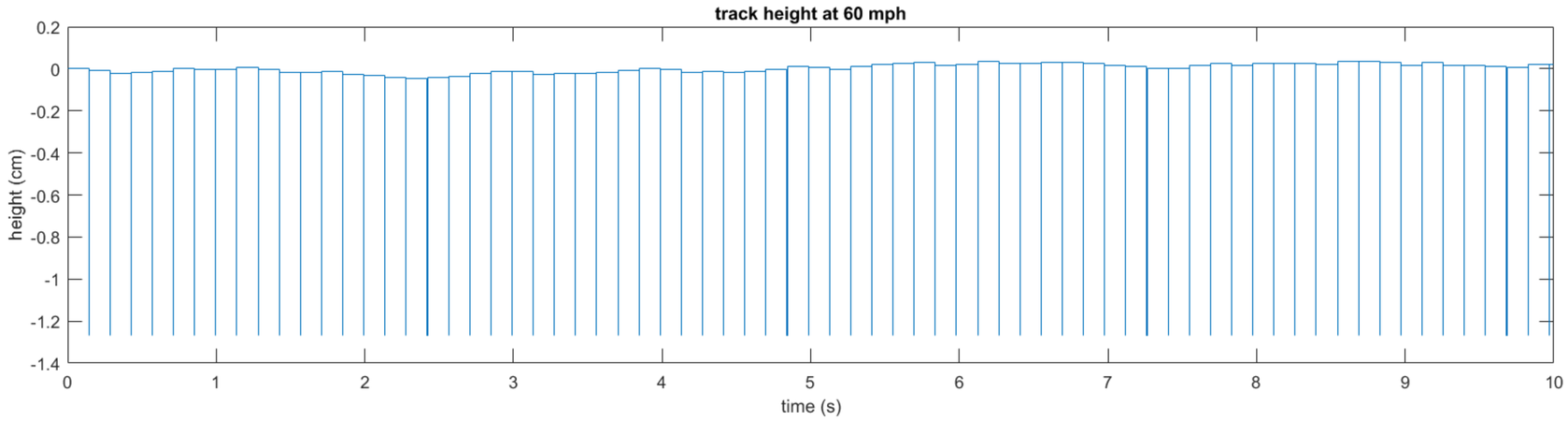
Stability | Lyapunov Functions

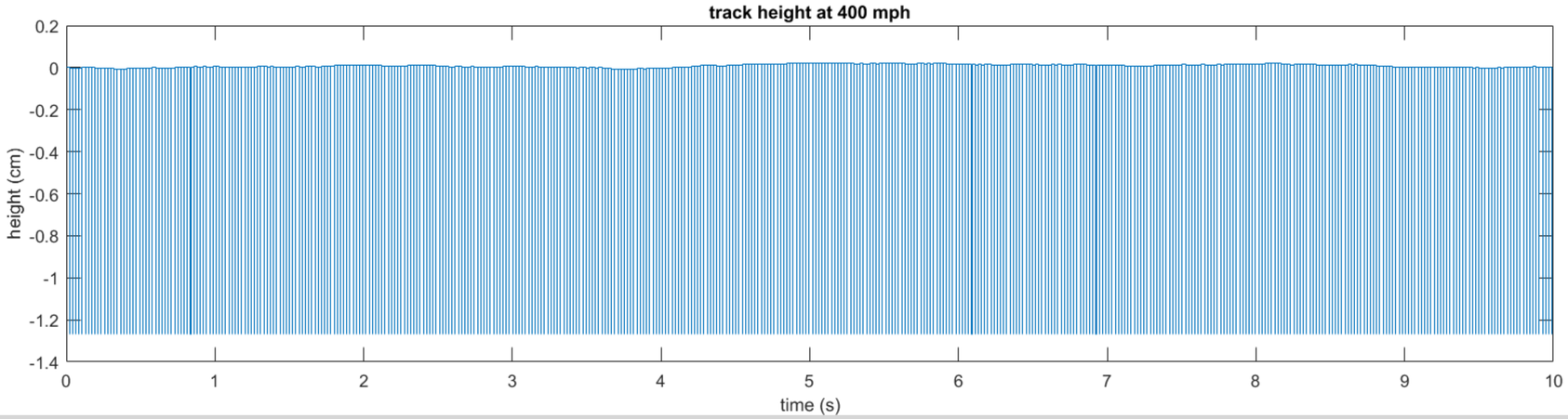
- **Provide an estimate to region of attraction**



Stability | **Disturbance:** Description

- **Track made up of separate plates**
  - **Height drift + gap between plates**





Stability | **Disturbance:** Equations

- **Two disturbances in system**
  - **Drift: changes equilibrium ride height (bounded, low energy, martingale)**
  - **Gap: additional skate area exposed to atmosphere (unbounded)**

$$M\ddot{z} = (P_{bag} - P_{atmo})A - Mg$$

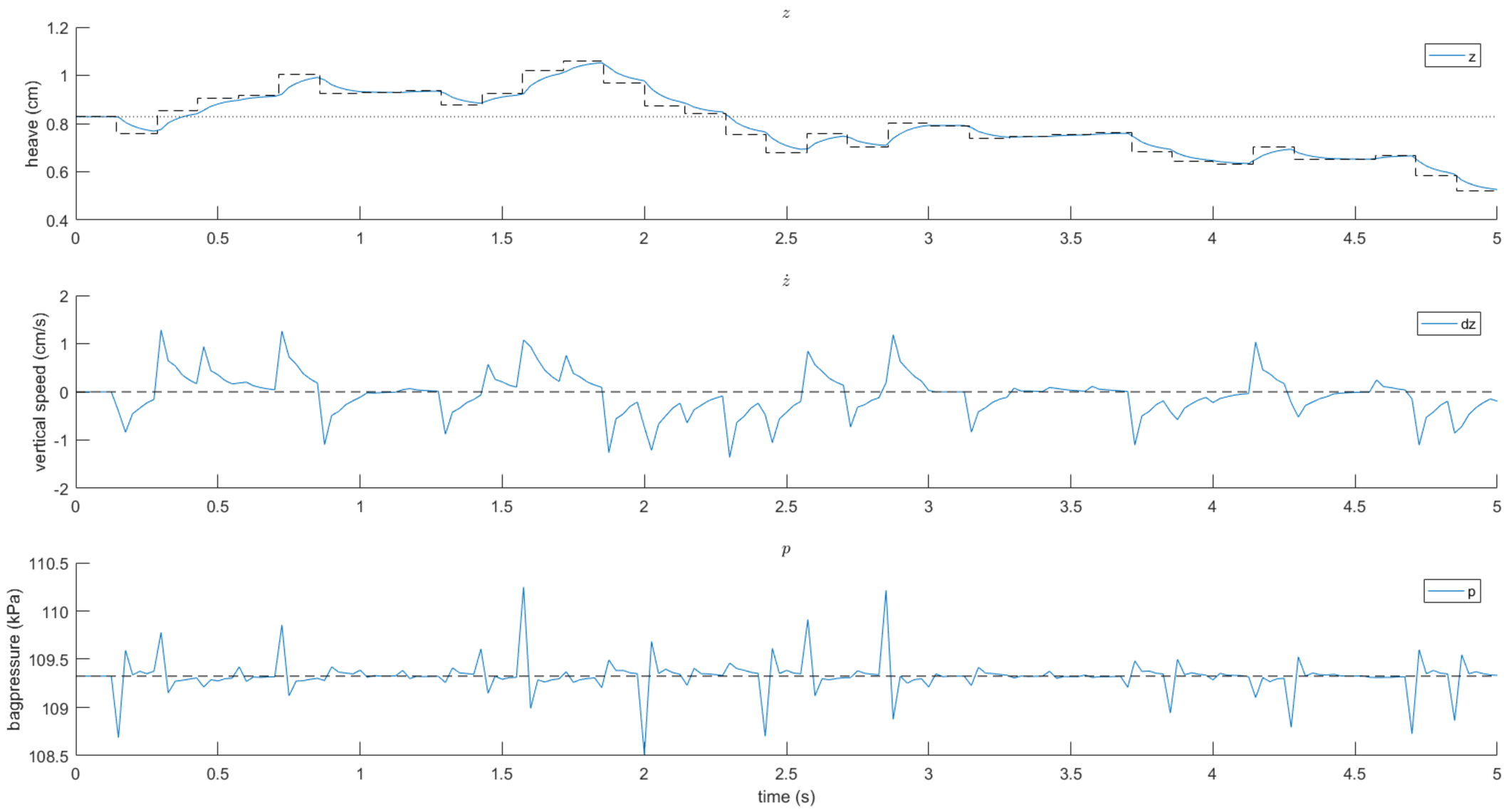
$$\dot{P}_{bag} = \frac{\gamma RT}{A(z + w_{height})}(\dot{m}_{in} - \dot{m}_{escape} - \frac{P_{bag}A\dot{z}}{RT})$$

$$\rho_{atmo}\frac{\partial P}{\partial x} = \beta(\frac{\dot{m}_{escape}}{A_e})^2 + \mu(\frac{\dot{m}_{escape}}{A_e})$$

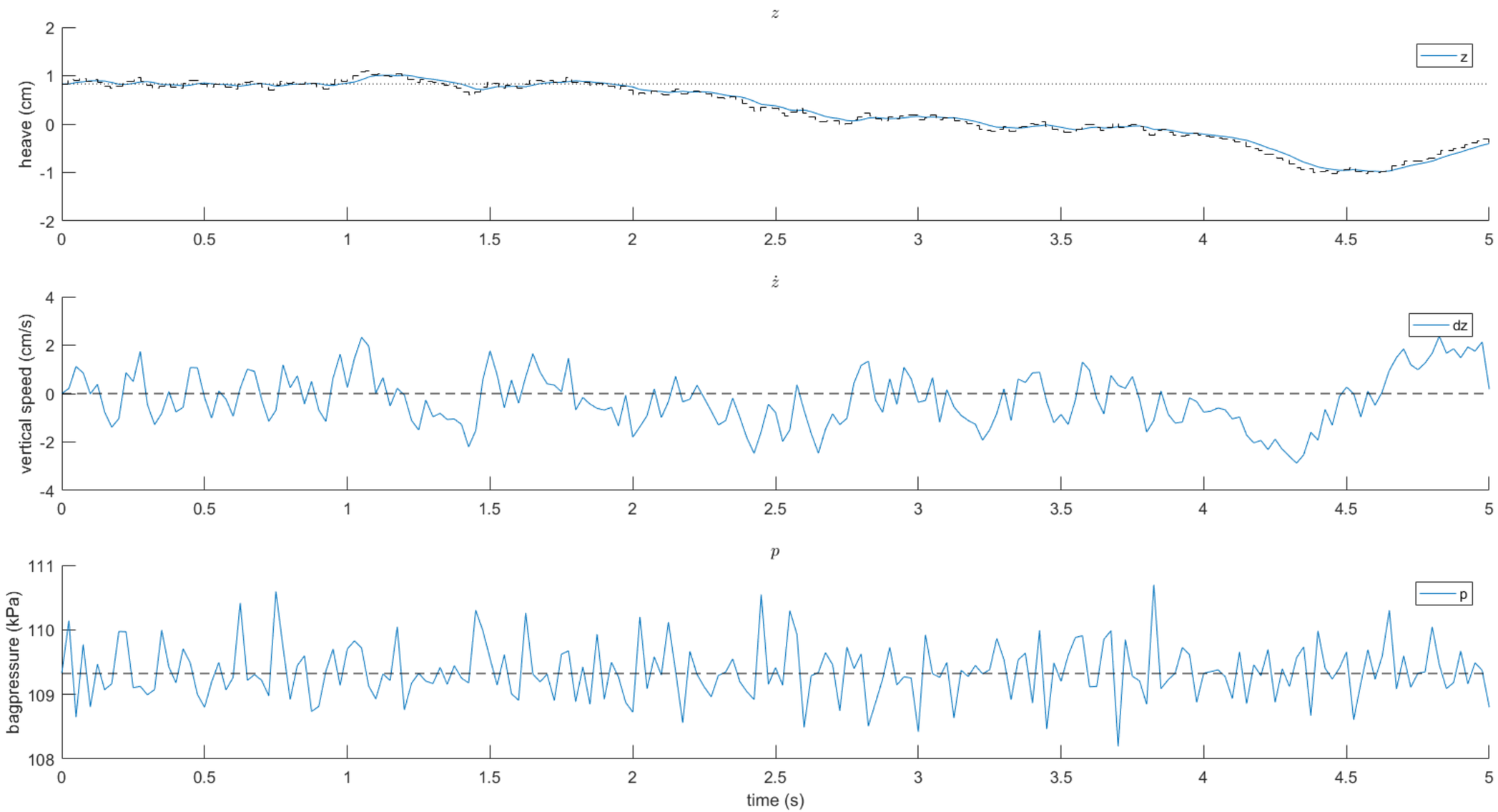
$$A_e = Per * (z + w_{height}) + W * w_{gap}$$

$$\frac{\partial P}{\partial x} = \frac{P_{bag} - P_{atmo}}{\ell}$$

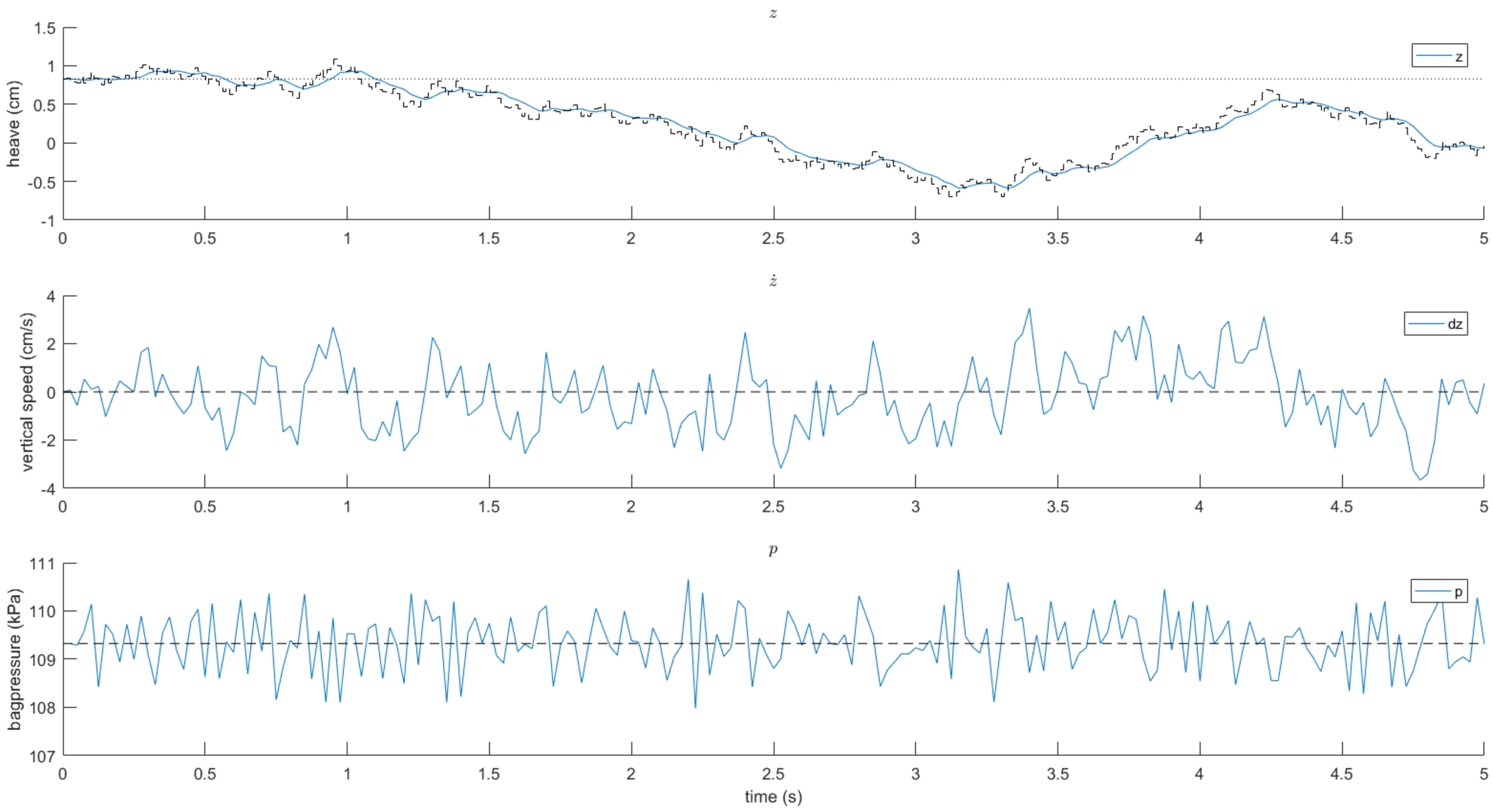
Stability | **Disturbance:** 60 mph



Stability | **Disturbance:** 400 mph

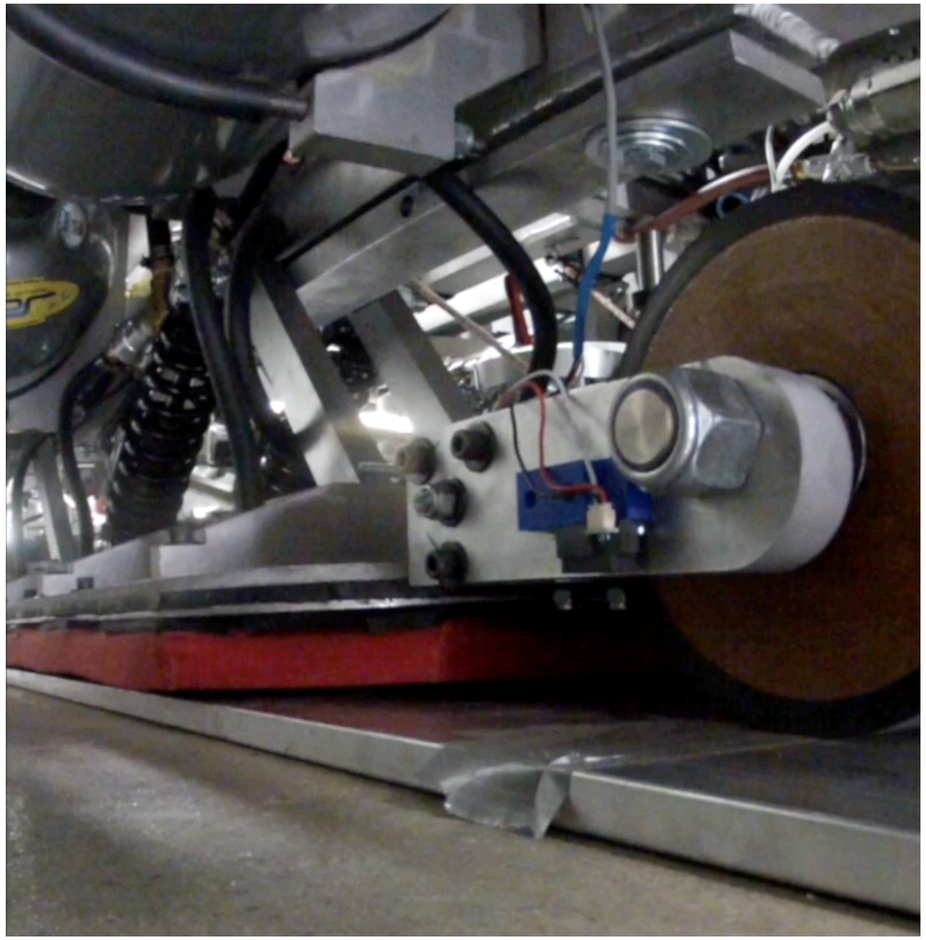


Stability | **Disturbance:** 700 mph



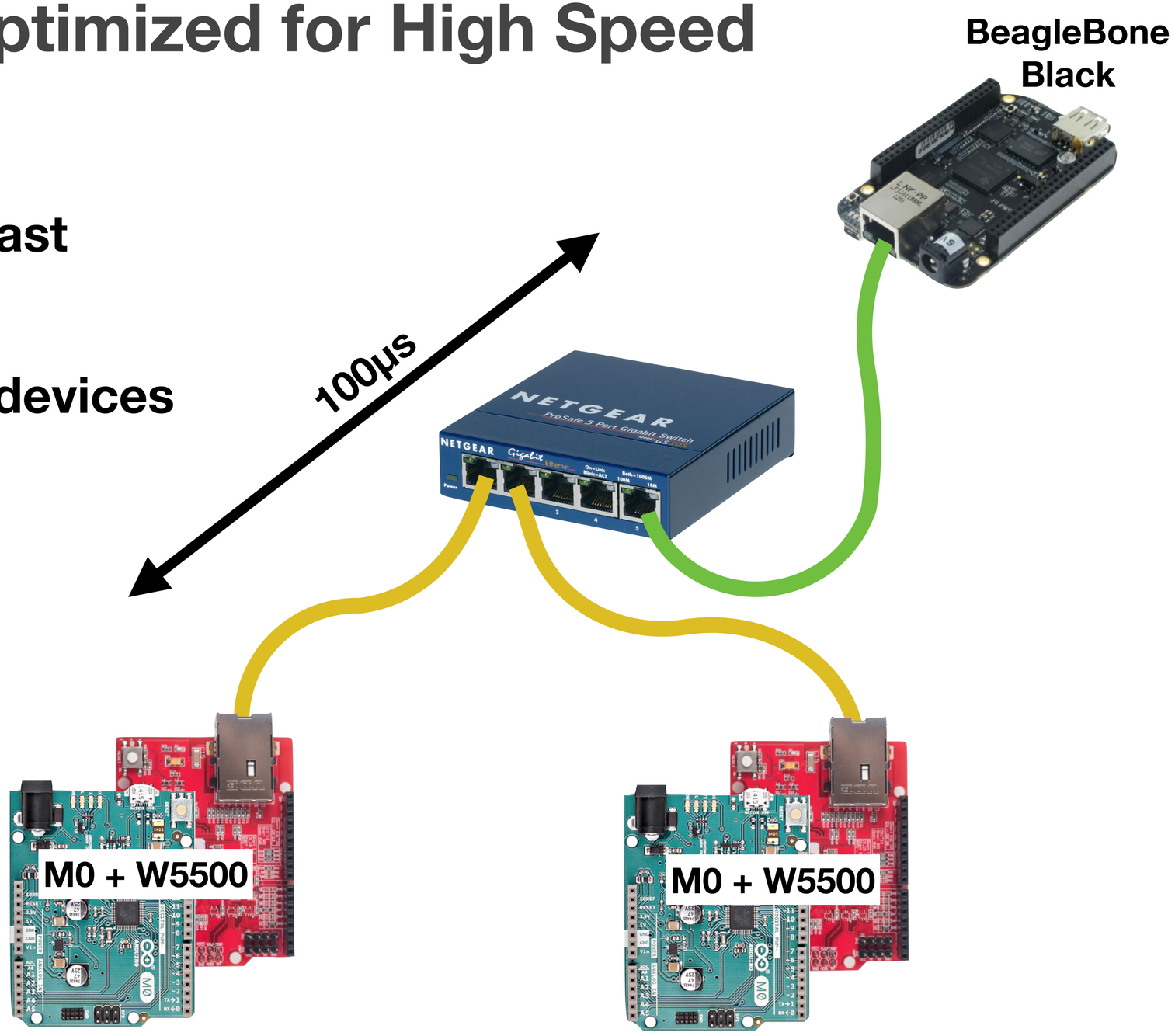
Stability | Issues with Model

- Open loop unstable in vacuum
- Linear control may result in finite escape time
- No spatial dependence
- No velocity (Navier-Stokes) considerations



Network Architecture | Optimized for High Speed

- "Talking stick" protocol
- Critical information is broadcast
- Ability to subscribe to events
- Time is synchronized across devices to maintain accuracy



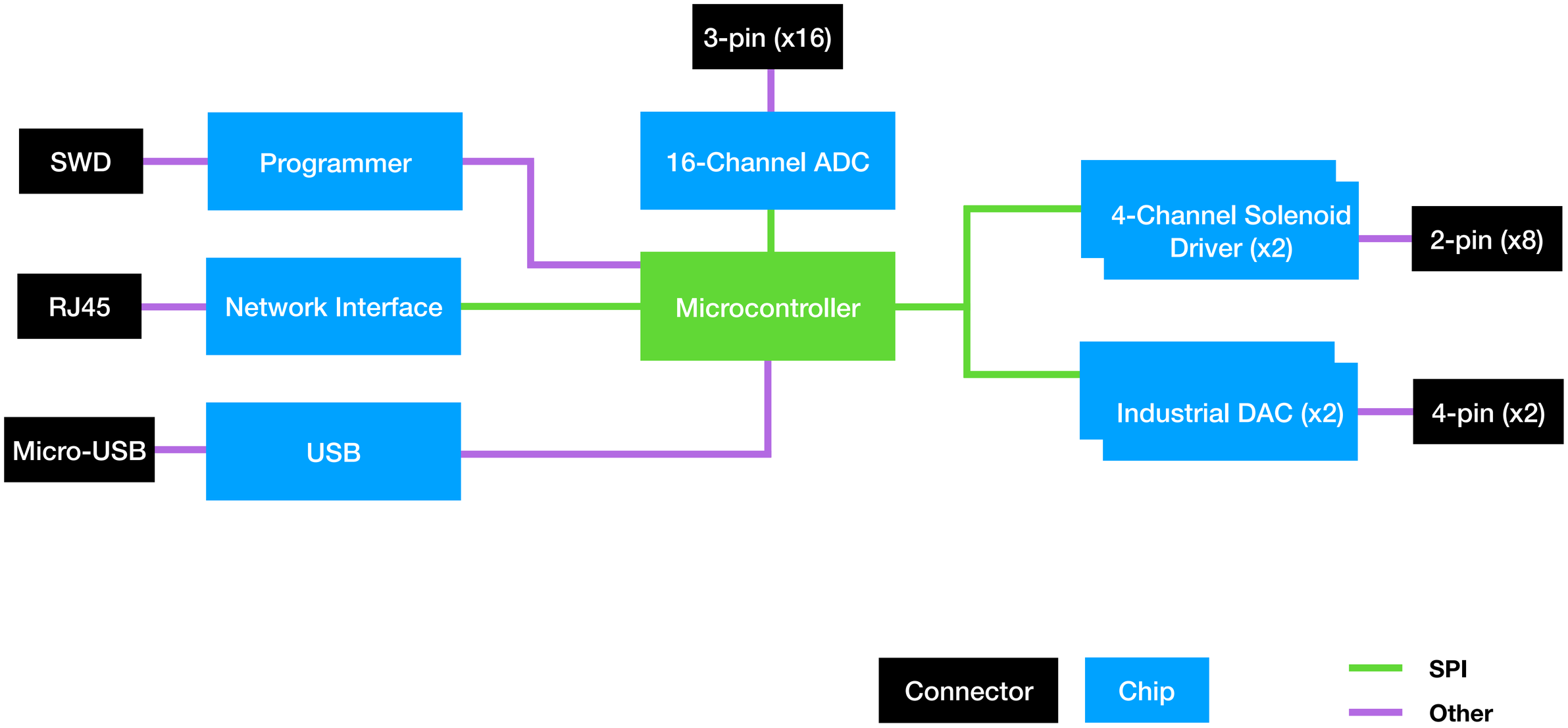
Prototyping | System Architecture

- Off the shelf hardware - Arduino M0, WizNet network interface, TP-Link switch
- Verification and testing
  - 100 µs average RTT (real-time network speeds)
- Software development
  - Hard timing requirements to achieve "Real time"
  - Architecture to allow for gathering, passing, and acting on sensing data
  - Final optimizations to account for various controls scheme without significant software development

Avionics System | Design Goals

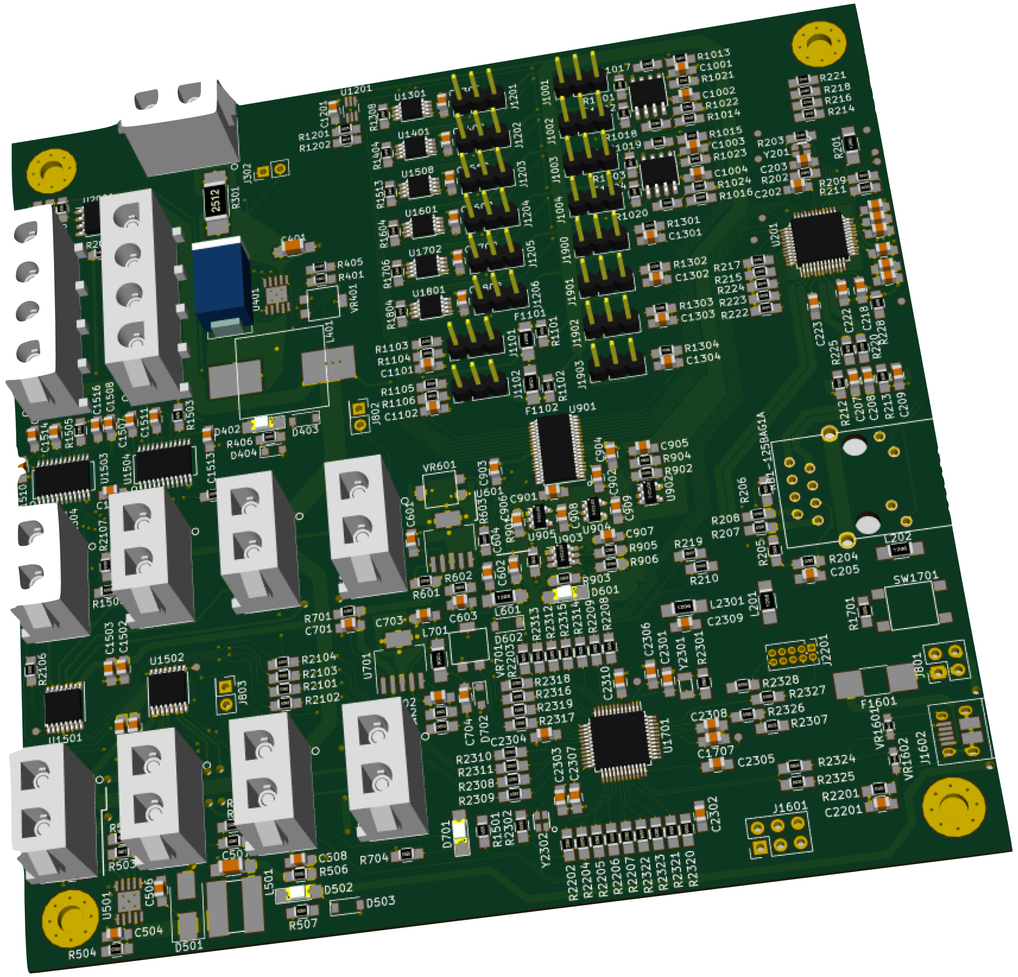
- **Based on off-the-shelf system**
  - Arduino M0 + WizNet W5500 shield
- **Sensors**
  - 16 analog inputs
  - Support for 0-5V, 0-24V, 4-20mA, and thermocouple
- **Actuators**
  - 8 solenoids
  - 2 proportional control (4-20mA or 0-5V)
- **Network Interface**
  - Realtime
- **Single power interface**
  - >27V
  - Regulators for 24V, 5V, 3.3V

Avionics Board | High Level



Avionics Board | Technical Challenges

- **Microcontroller**
  - Serial bus peripherals
  - Clock domains
  - Hardware timers
- **Board size**
  - Smallest size is best for pod
  - Challenges for component placement
- **High-speed routing**
  - 2-layer board
  - Minimize breaks in ground plane



Logistics | Cost Effectiveness

	Manufacturer	Product	Channels	Resolution	Cost
DAC	DGH Corp	D6500	2	N/A	$295.00
Solenoid	Advantech	ADAM-4168	8	N/A	$170.00
ADC	Arduino	Arduino Mega	16	10-bit	$38.50
Network	Wiznet	5500 Ethernet Shield	N/A	N/A	$23.00
Processor	Arduino	M0	N/A	N/A	20
			Total		**$546.50**

- **Custom BOM: $160**
- **5 PCBs with shipping: $50**
- **Total: $210**

Questions?