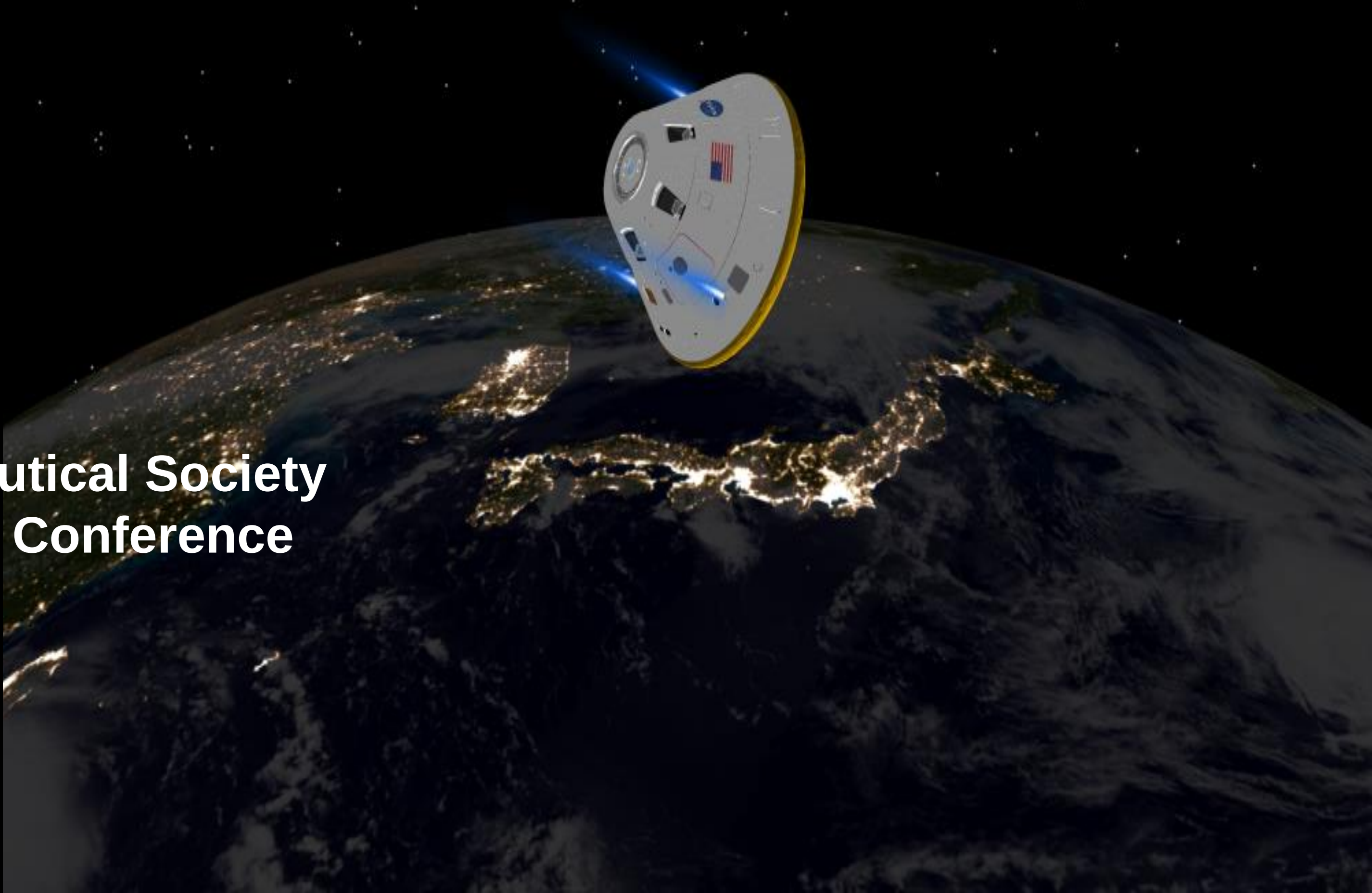
ORION GN&C DETECTION AND MITIGATION OF PARACHUTE PENDULOSITY



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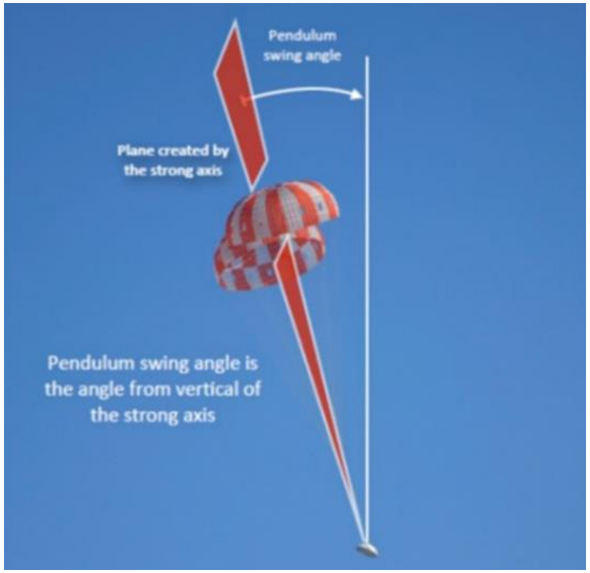
Pendulosity

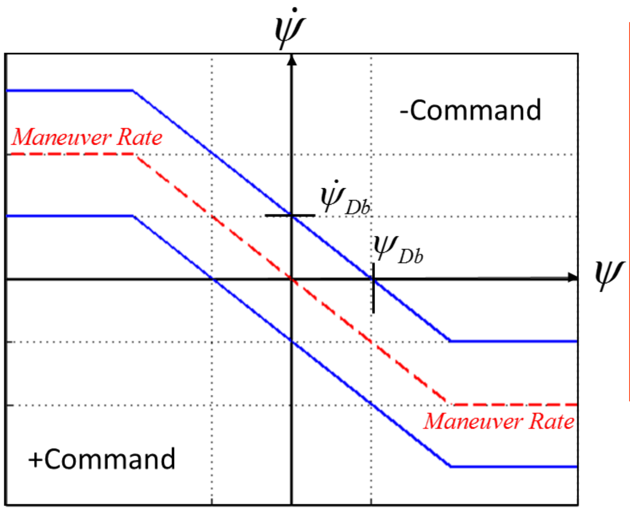
Late in the Orion parachute development program, Capsule Parachute Assembly System (CPAS) drop tests exhibited pendulous swing mode of the crew module (CM).

- Increases touchdown impact loading to the structure and crew
- Can saturate the reaction control system (RCS) during final alignment of the CM
- A multidisciplinary team was created to mitigate risk for future Orion missions.

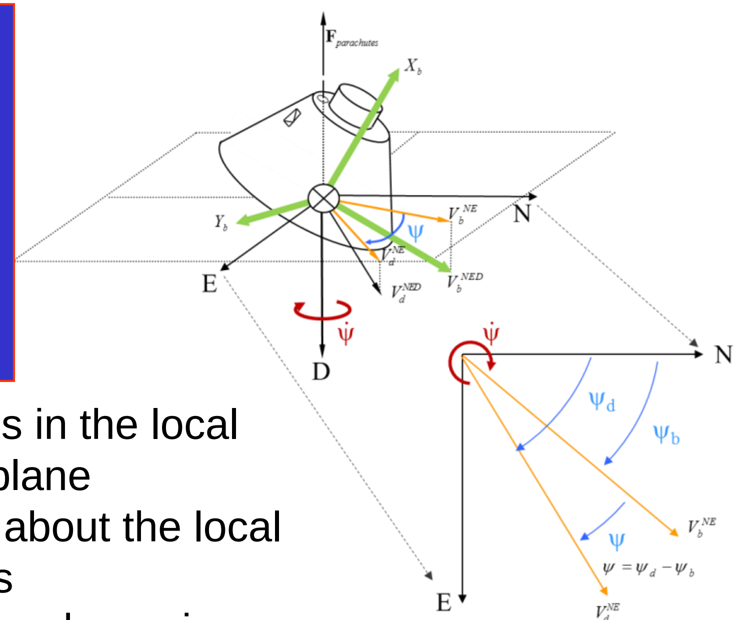


Pendulous motion is present with three chutes but only grows to large swing amplitudes in two-chute scenarios (single failure)

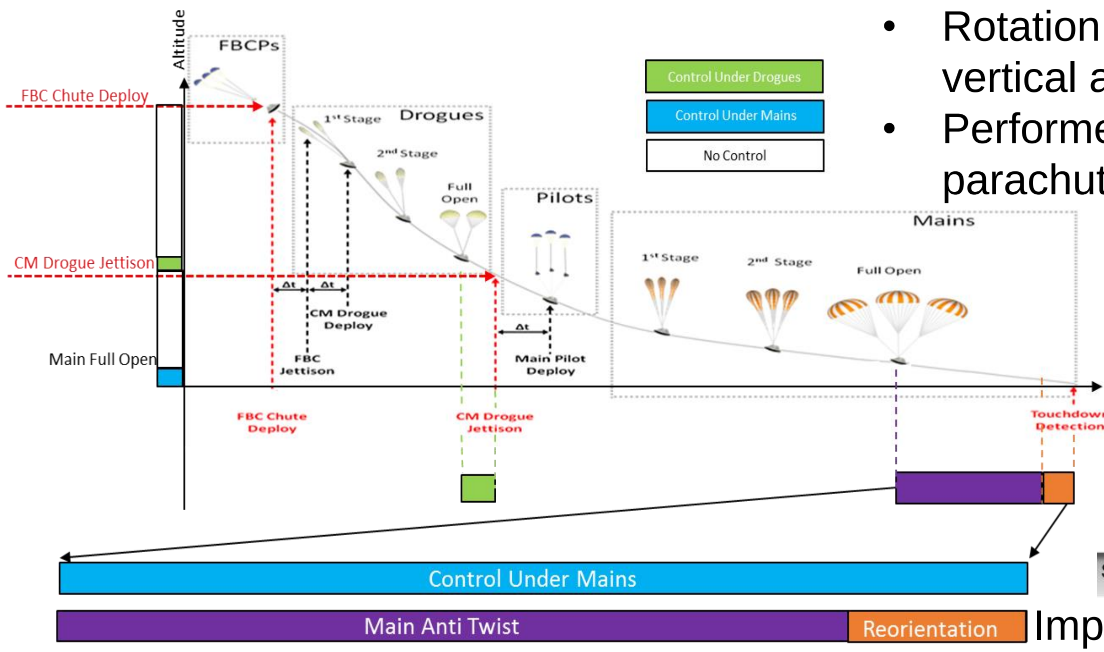
Final Alignment: Touchdown Heading Control

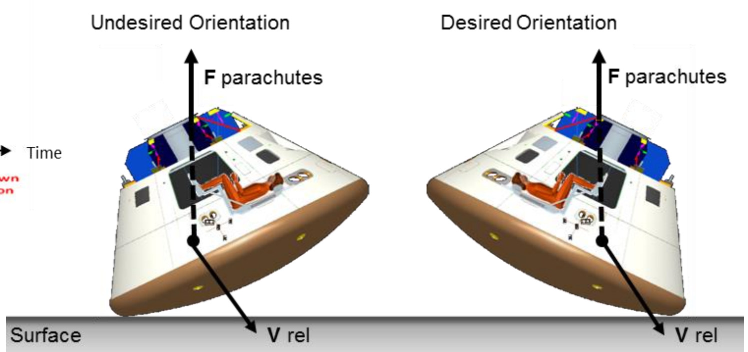


Touchdown heading control aligns the CM with the direction of horizontal velocity to reduce touchdown impact loading on the crew and structure.



- Alignment is in the local horizontal plane
- Rotation is about the local vertical axis
- Performed under main parachutes



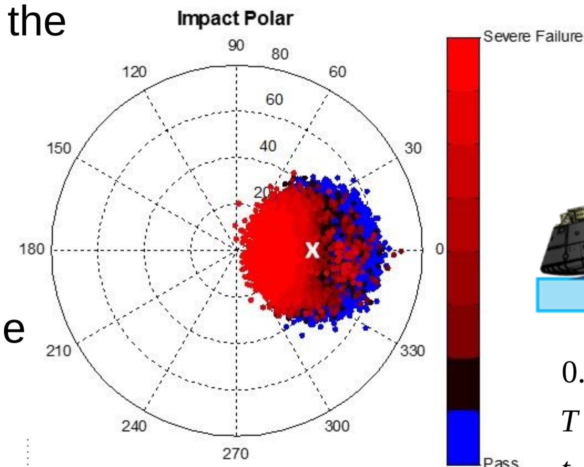


Impact occurs with crew situated feet-forward

Pendulosity Effects

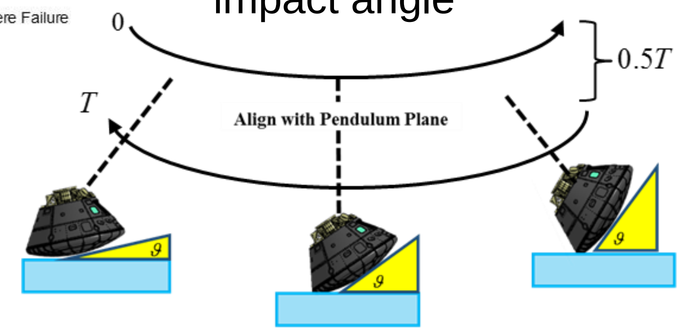
Disturbs horizontal velocity:

- Control Saturation
  - Control is unable to track the rapid changes in heading
- Improper alignment at touchdown
- Heading sensitivity to pendulum increases as horizontal velocity magnitude decreases



Modifies CM attitude:

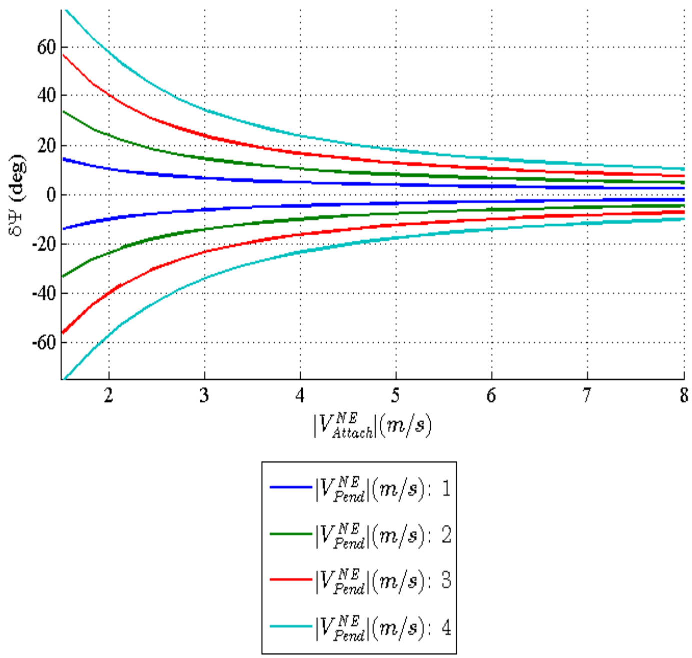
- Increased distribution of impact angle



$0.5T << t_{180}$

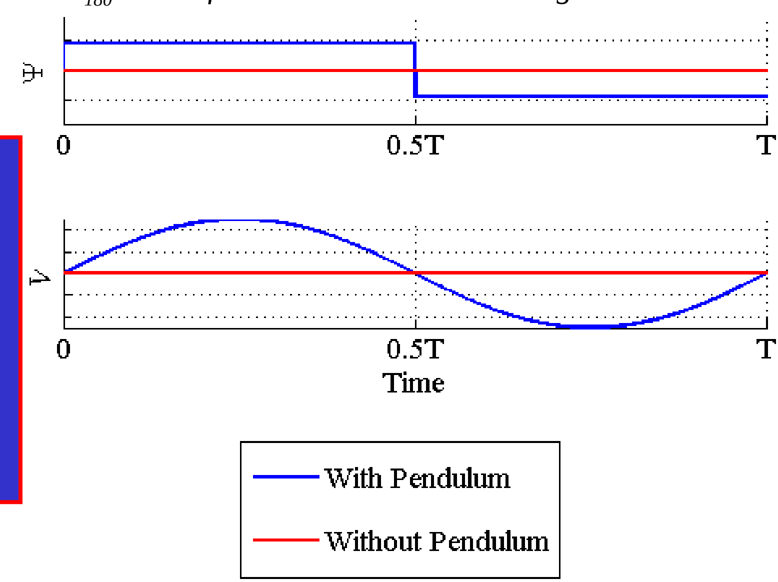
T :*Pendulum Period*

t_{180} :*Time for RCS to manuver 180 degrees*

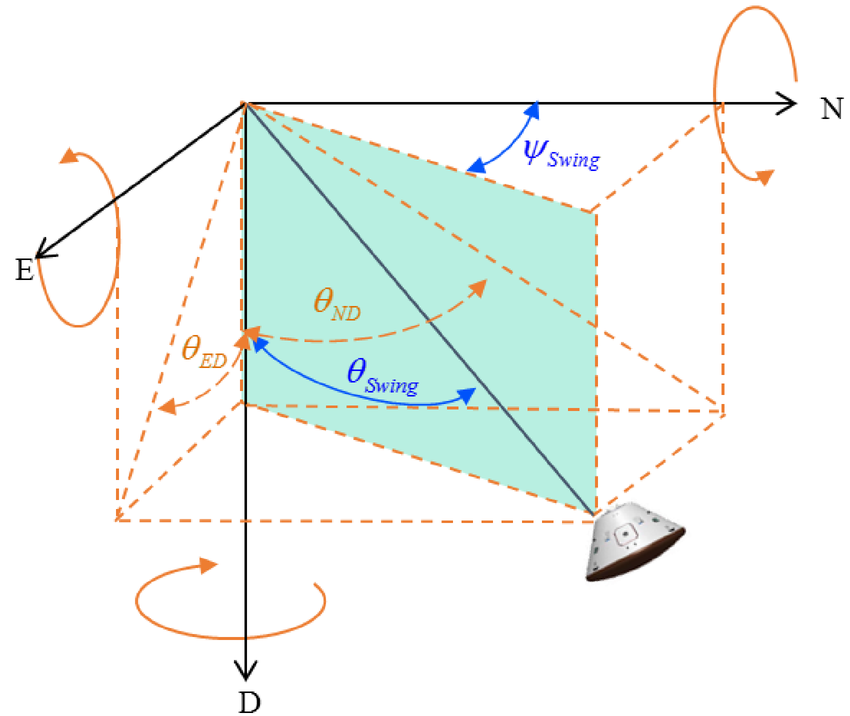


Impact loading increases with:

- **Misalignment to velocity**
- **Low impact angles**



Observing Pendulum Motion



- **Swing angle is found geometrically:**

$$\theta_{Swing} = \sin^{-1}\left(\sqrt{\sin^2(\theta_{ND}) + \sin^2(\theta_{ED})}\right)$$

- **Pendulum energy is found algebraically:**

$$E_{Pend} = \frac{1}{2} mL^2 \left(\dot{\theta}_{ND}^{\ 2} + \dot{\theta}_{ED}^{\ 2}\right) + mgL\left(1 - \cos(\theta_{Swing})\right)$$

- **Swing plane angle is found geometrically and limited to be within +/- 90 degrees:**

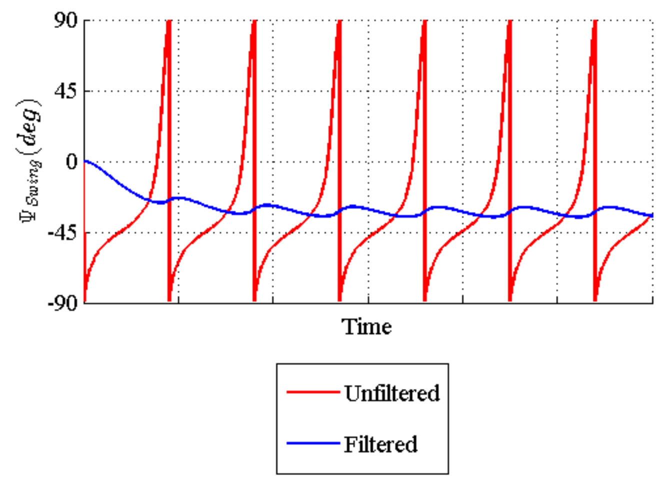
$$\psi_{Swing} = \tan^{-1}\left(\frac{sign(\theta_{ND})\sin(\theta_{ED})}{\left|\sin(\theta_{ND})\right|}\right)$$

- **Pendulum swing is highly elliptical (not planar) requiring that the geometric swing plane angle be filtered**

Desired Outputs:

- Attach Point (Chute Cluster/Wind) Velocity
- Pendulum energy
- Swing plane angle

Two Luenberger observers are used independently to obtain state estimates in the N-D and E-D planes



Observing Pendulum Motion (2D)

Orion Project

State Definitions:

$$x = \begin{bmatrix} \theta & \dot{\theta} & V_{Attach} \end{bmatrix}^T$$

$$\dot{x} = \begin{bmatrix} \dot{\theta} & \ddot{\theta} & a_{Attach} \end{bmatrix}^T$$

Control Input:

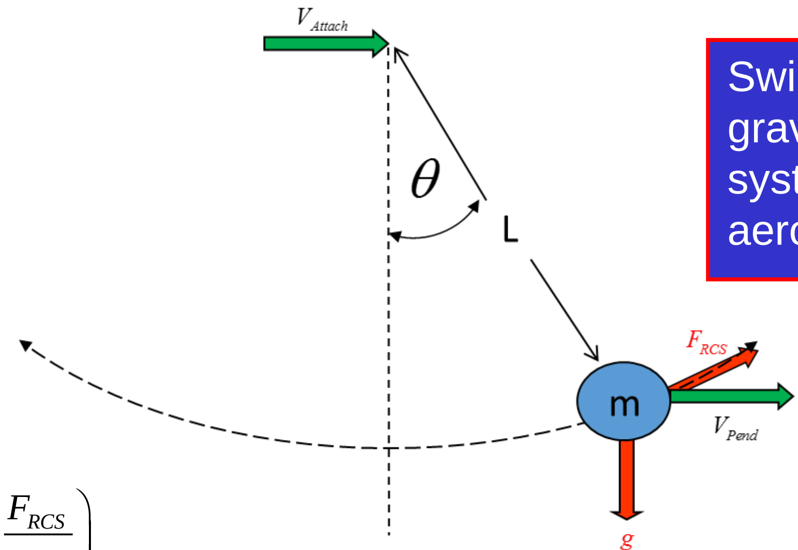
$$u = F_{RCS}$$

Equations of Motion:

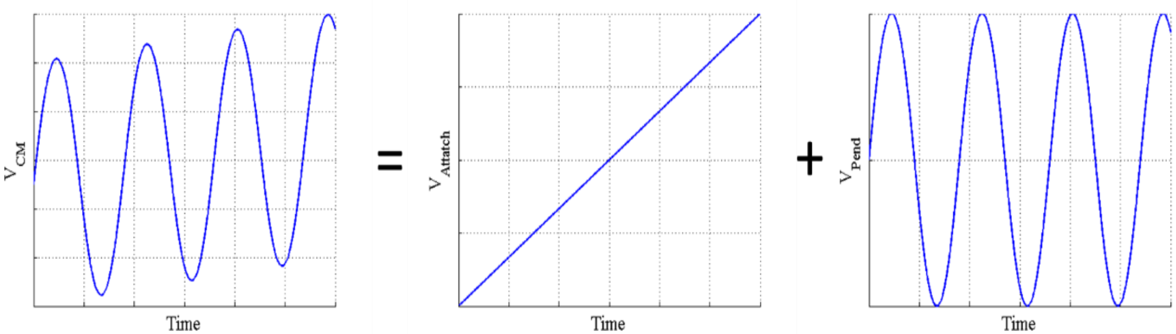
$$\ddot{\theta} = \frac{1}{L}\left(-g\sin(\theta) - a_{Attach}\cos(\theta) + \frac{F_{RCS}}{m}\right)$$

Measurement Equation:

$$y = V_{CM} = V_{Attach} + L\dot{\theta}\cos(\theta)$$



Swing is modeled as a simple gravity pendulum. In flight the system is forced by parachute aerodynamic forces.



Total velocity is assumed to be a combination of the underlying wind velocity and the pendulum induced velocity.

Luenberger Observer:

$$\dot{x} = Ax + Bu + G(y - Cx)$$

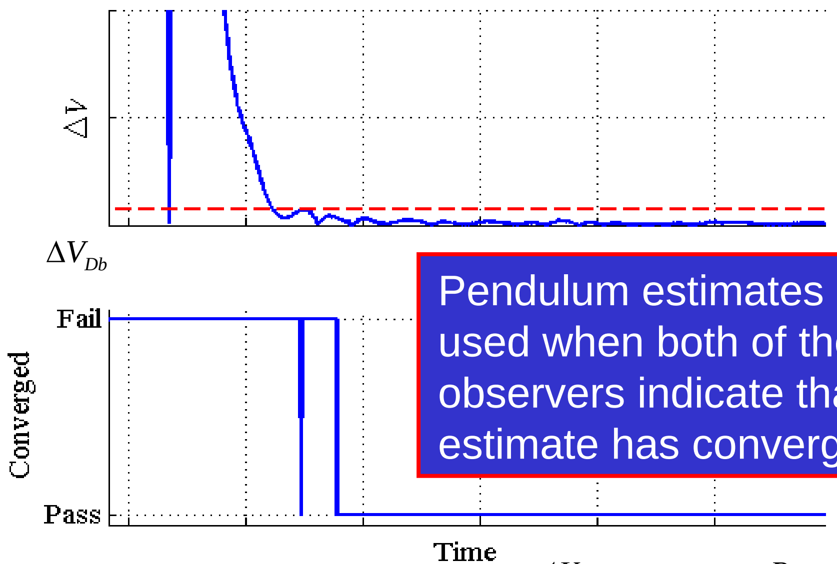
$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-g}{L} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{L^2 m} \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & -L & 1 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix}$$

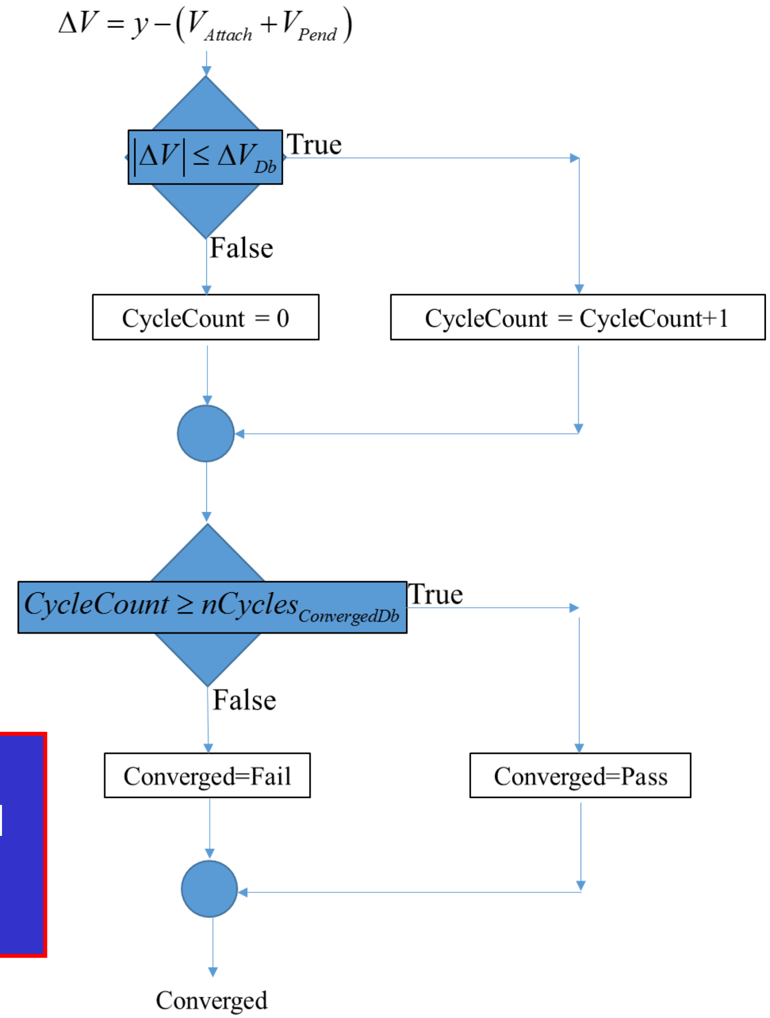
Observer Estimate Quality Check

A convergence check is performed to output an indication that the observer estimate is valid

- Prevents undesirable behavior during observer initialization
- Protects against erroneous measurements
  - Filtered swing plane estimates are only updated if the estimate is indicated as valid
- Protects against unknown errors that result in a diverging estimate



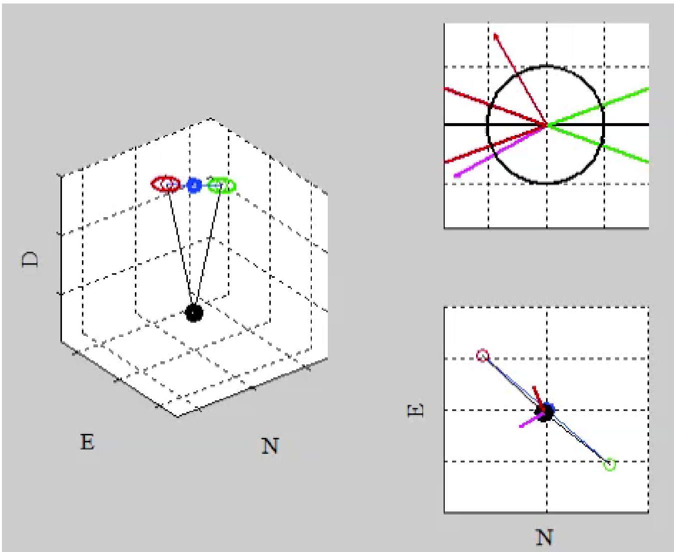
Pendulum estimates are only used when both of the internal observers indicate that their estimate has converged

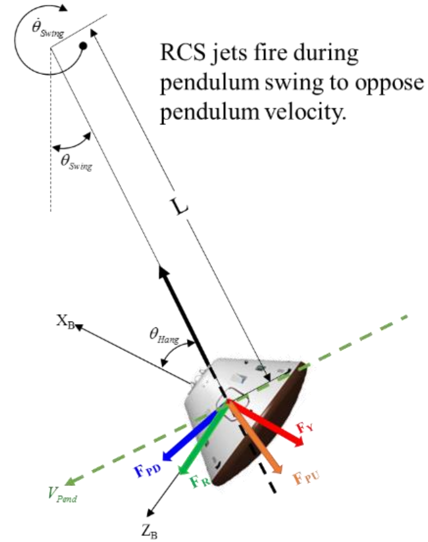


ΔV_{Db} : *Parameter indicating the maximum residual when converged*

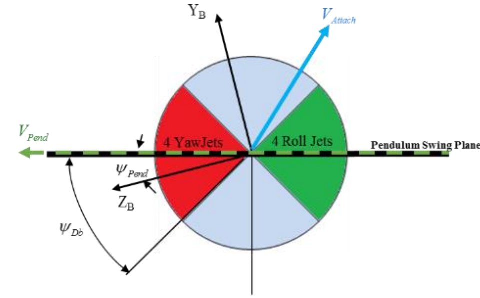
$nCycles_{ConvergedDb}$: *Parameter indicating the number of cycles required before declaring convergence*

Pendulum Damping





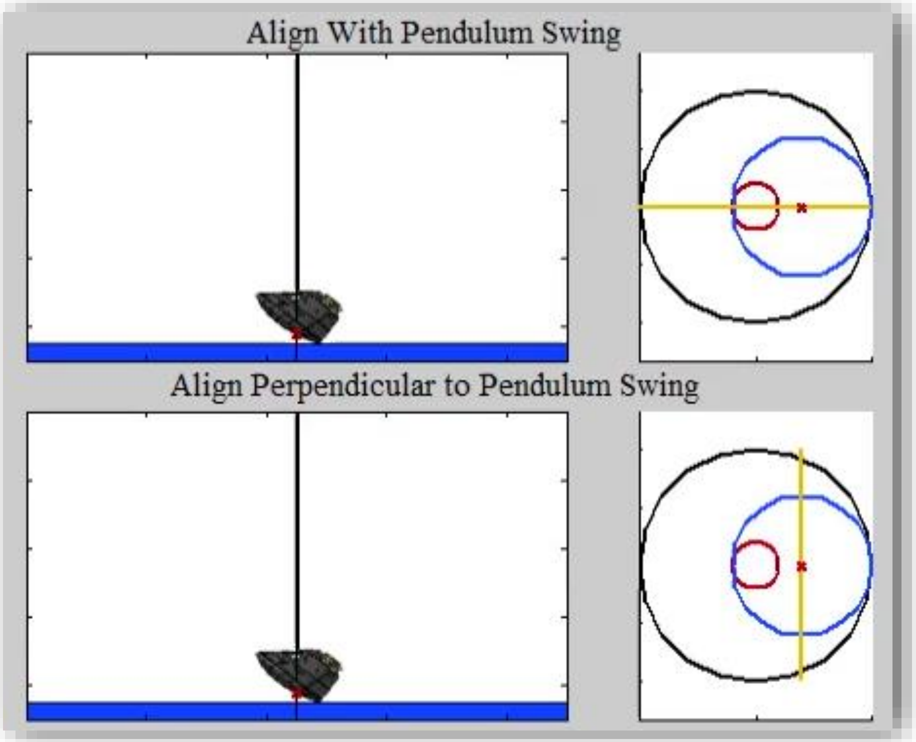
Control Alignment with Pendulum Plane

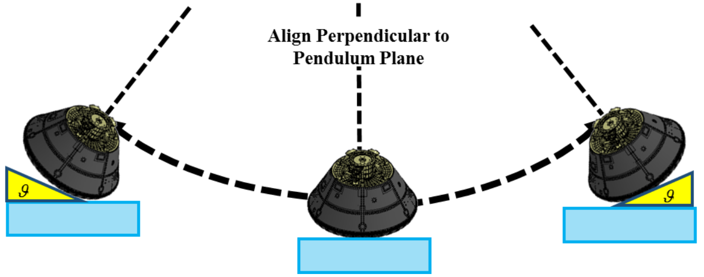


Pendulum damping abandoned due to marginal reduction in touchdown impact loading at a high propellant cost and algorithm complexity.

- **Limited time**
- **Limited control authority**
  - Non-ideal jet location
  - Undersized jets for this application
- **Addition of a swing angle rate estimate**
  - Phasing of thruster firings
  - Complicated by non-planar swing
- **Pendulum swing plane may not be coincident with velocity**
  - Reserve time to reorient the CM prior to touchdown impact
- **Algorithm Complexity**
- **Limited propellant**
  - Damping allowed until remaining propellant depleted to a minimum reserve threshold
    - Requires an estimate of remaining propellant
- **Alignment to the swing plane**
  - Accuracy of the swing plane angle estimate
  - Active alignment – Large propellant cost
  - Passive alignment – Limited opportunity for damping to occur

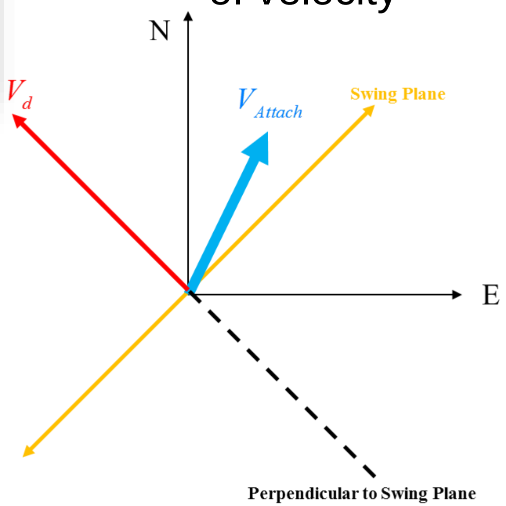
Alternate Heading

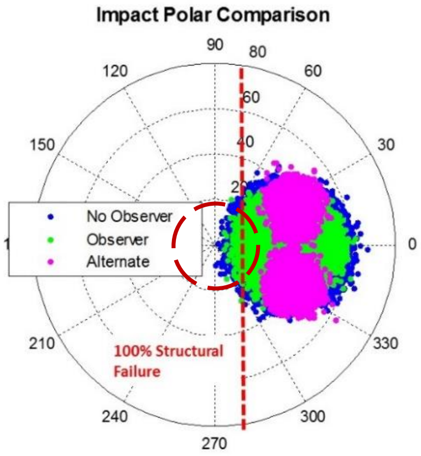




Align the CM to be perpendicular to the swing plane

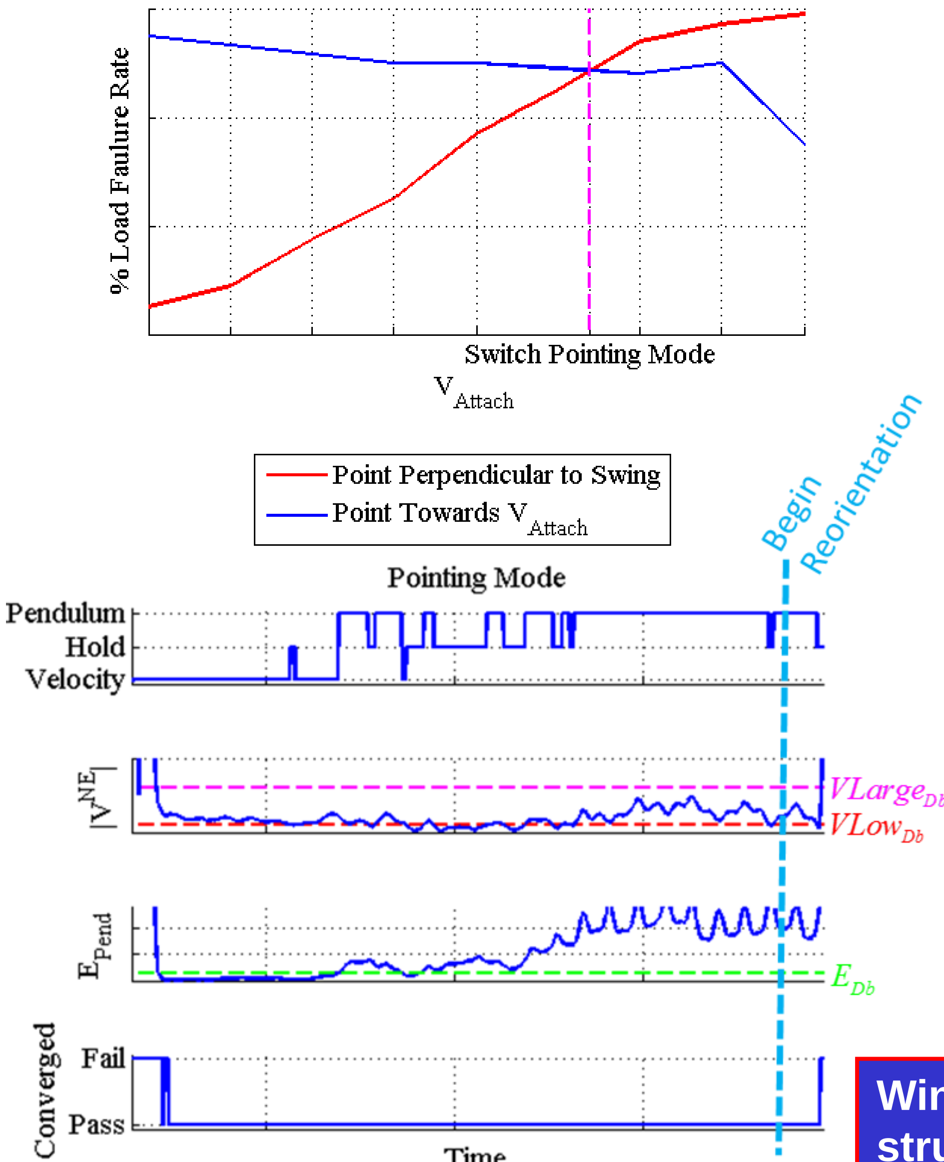
- The swing plane and velocity direction may not be coincident
- Choose perpendicular direction that minimizes the angle to the direction of velocity





Aligning the vehicle so that it is pointed out-of-plane with respect to the swing plane reduces the probability of a low impact angle at touchdown

Pointing Mode Selection



Pointing Modes:

- **Pendulum**
  - Point perpendicular to the swing plane nearest the direction of horizontal velocity if:
    - Detected Pendulum Energy is above a specified threshold
    - Horizontal velocity magnitude is below a specified threshold
  - Stay in this mode (latch) if:
    - Landing reorientation has begun
- **Velocity**
  - Point in the direction of horizontal velocity
  - Default mode
- **Hold**
  - Hold the previous pointing direction if:
    - Horizontal velocity magnitude falls below a specified threshold
    - Pendulum pointing has been latched and the observer diverges

Wind alignment becomes the driver to structural loading at higher velocities

Conclusions and Acknowledgements

- **Pendulum induced dynamic increase loading to the crew and CM structure**
  - Pendulum motion is driven by parachute aerodynamics
  - Energy can be input, or removed, from the system at any time by the parachutes
- **Pendulum observer is able to produce accurate estimates of the pendulum state**
  - Models pendulosity as a simple gravity pendulum
- **Pendulum damping did not show significant improvement in loading success probability**
  - Insufficient control force available from CM RCS
  - High propellant cost
  - Significant algorithm complexity
  - Able to reduce peak swing amplitudes in some situations
- **Pointing the vehicle in a direction perpendicular to the swing plane reduces probability of low impact angles at touchdown**

GN&C has successfully developed an algorithm to mitigate the effects of pendulosity for the Orion spacecraft.

- Software solution avoids costly parachute or vehicle structure design changes
- Monte Carlo analysis with high-fidelity GN&C simulations have demonstrated a 35% improvement in load success probability

The authors wish to acknowledge the technical contributions of the entire Orion GN&C team at NASA, Lockheed Martin, and respective contractors.

QUESTIONS?