Pitch Axis Control for a Guided Projectile in a Wind Tunnel-based Hardware-In-the-Loop Setup

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Presentation outline

- **The ACHILES Experimental Setup**
- **Modeling and Identification**
- **Autopilot Design**
- **Experimental Validation**
- **Conclusion**

The ACHILES Experimental Setup

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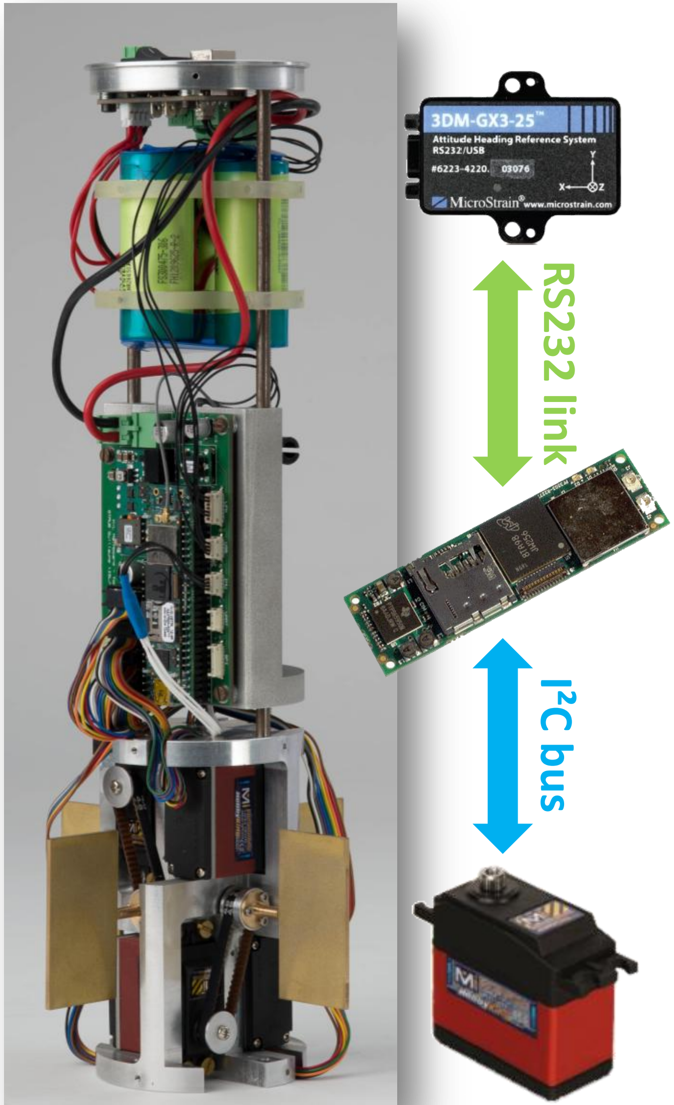
Automatic Control Hardware-In-the-Loop Experimental Setup

- **Controlled environment for projectile model estimation and autopilot testing/validation**
  - Low-cost, realistic alternative to free-flight testing for projectile identification and testing
- **Key components :**
  - Autonomous guided projectile prototype
  - Subsonic wind tunnel
  - 3-DoF gimbaled structure
- **Missile-like structure**
  - Tail fins for stabilization
  - 4 front-located guidance canards

Development computer

Embedded hardware



Inertial Measurement Unit

- 3 accelerometers, 3 gyros, 3 magnetometers
- Embedded sensor fusion algorithm
- 100Hz update rate

Embedded Computer

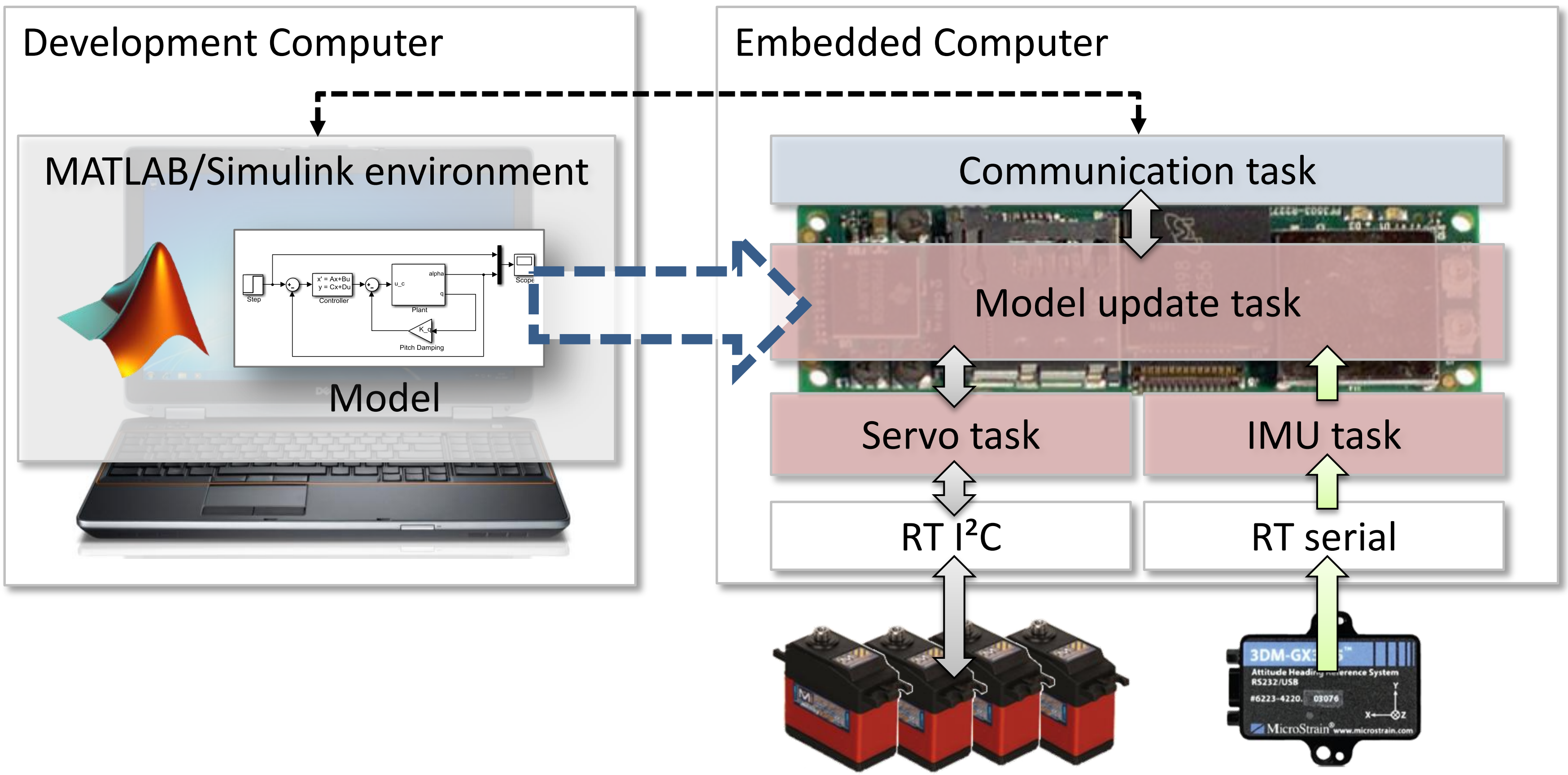
- Gumstix SBC running realtime Linux distribution
- 700MHz Cortex-A8 with 512MB RAM
- WiFi chipset, I²C, SPI and UART bus

Control fin actuators

- RC servos with custom control board
- 0.09° resolution
- 100ms response time
- Linear response from -30° to +30°

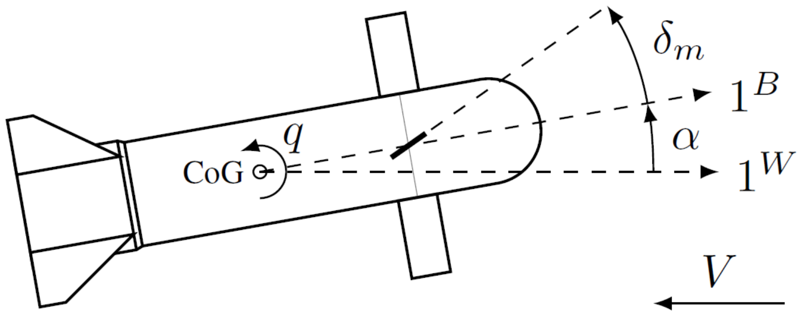
Embedded software

- 100Hz execution rate, low latency I/O requirements
- Embedded Realtime Linux distribution based on Xenomai and Emdebian



System Modeling

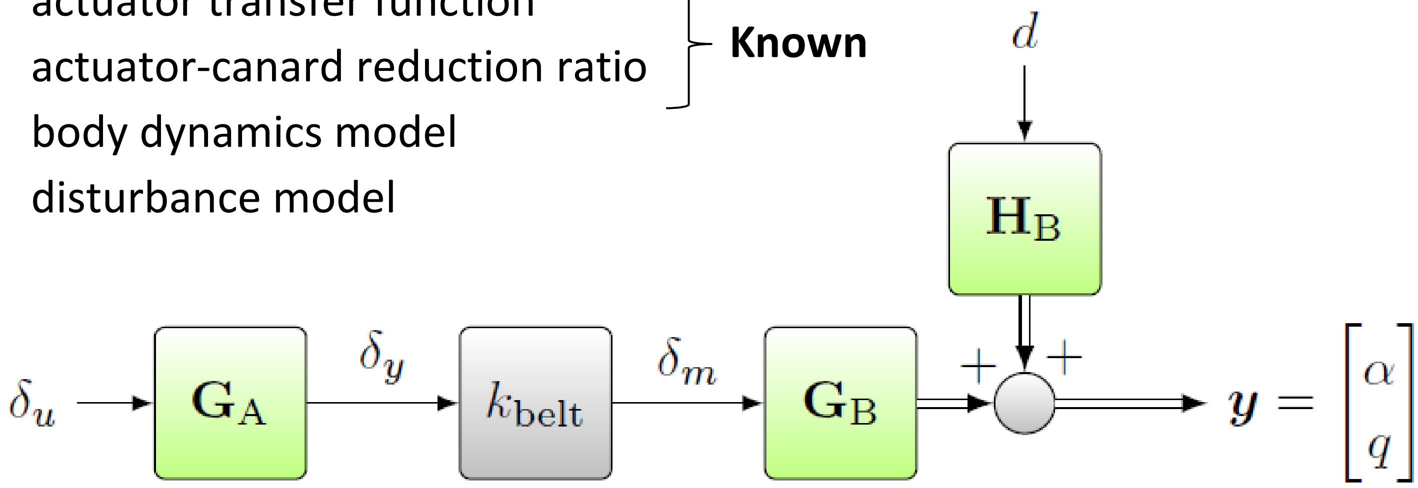
- **Only the pitch axis motion is considered**
  - Other axes are locked to zero
  - Constant airspeed (V = 25 m/s)



- **No sensor model**
  (IMU bandwidth >> system bandwidth)

- **Pitch dynamics open-loop chain :**
  - G_A: actuator transfer function
  - K_{belt}: actuator-canard reduction ratio
  - G_B: body dynamics model
  - H_B: disturbance model

Known (G_A, K_{belt})



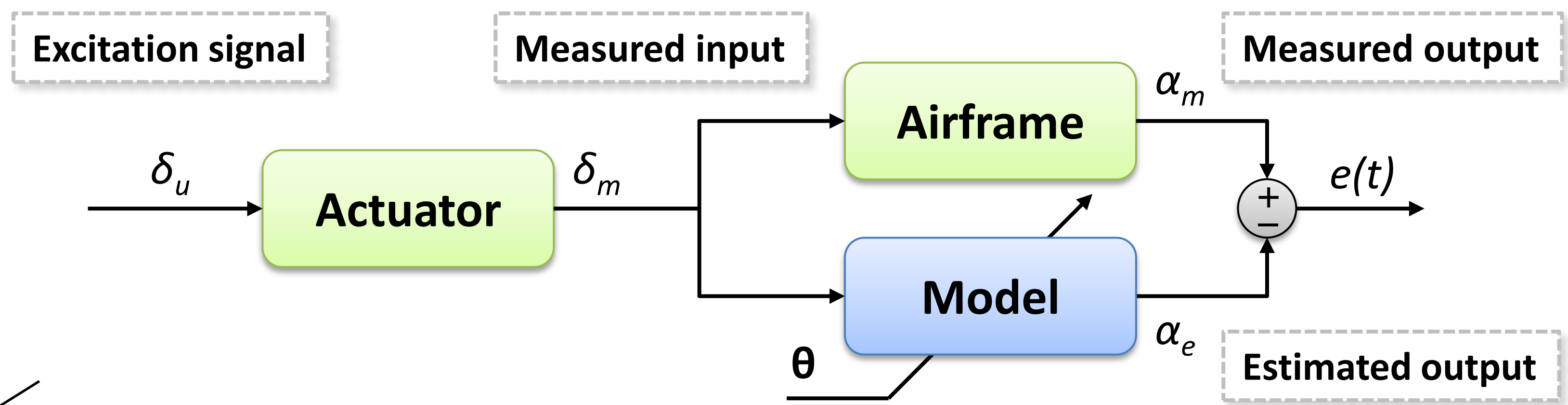
System Identification

- Airframe dynamics governed by flight mechanics
- Linearized around a family of equilibrium (trim) points
- Written in Directly Parametrized Innovations Form:

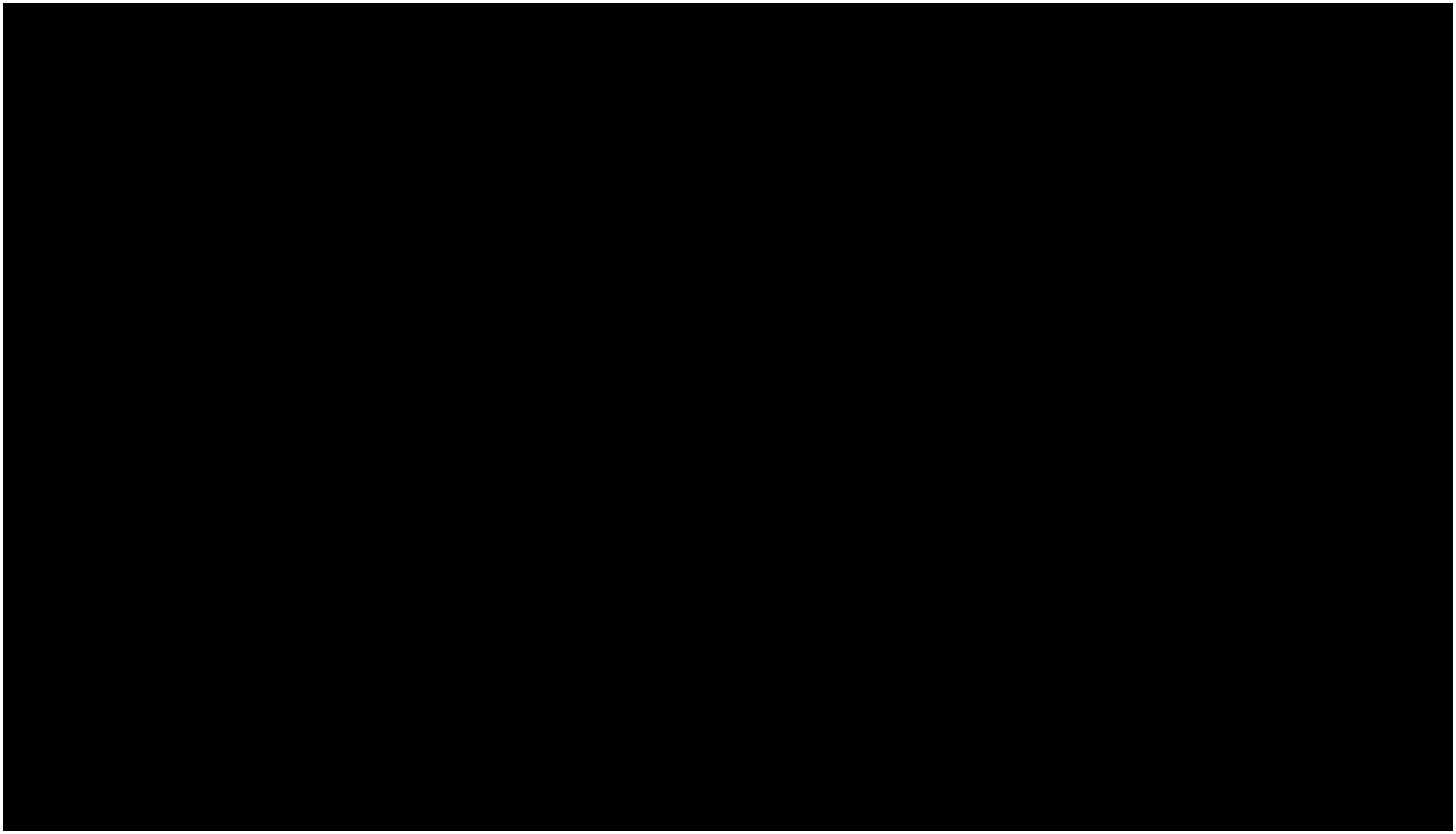
$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ M_{q\alpha} & M_{qq} \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ M_{q\delta} \end{bmatrix} u + \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} e$$

Linearized Airframe Dynamics

Disturbance Dynamics



Data collection experiment



Estimation Results

α_{Trim}	$M_{q\alpha}$	$\Delta M_{q\alpha}$	M_{qq}	ΔM_{qq}	$M_{q\delta}$	$\Delta M_{q\delta}$	Fit
0°	50.3	6%	2.9	15%	38.8	6%	74%
1°	53.0	9%	2.7	20%	34.3	10%	75%
2°	54.6	7%	2.8	16%	36.2	7%	82%
3°	56.1	2%	2.6	8%	40.8	3%	86%
4°	52.5	4%	2.4	12%	40.5	4%	89%
5°	51.5	5%	2.2	15%	40.3	5%	89%
6°	52.7	3%	2.1	17%	41.5	4%	89%
7°	54.4	3%	2.0	8%	38.5	3%	86%

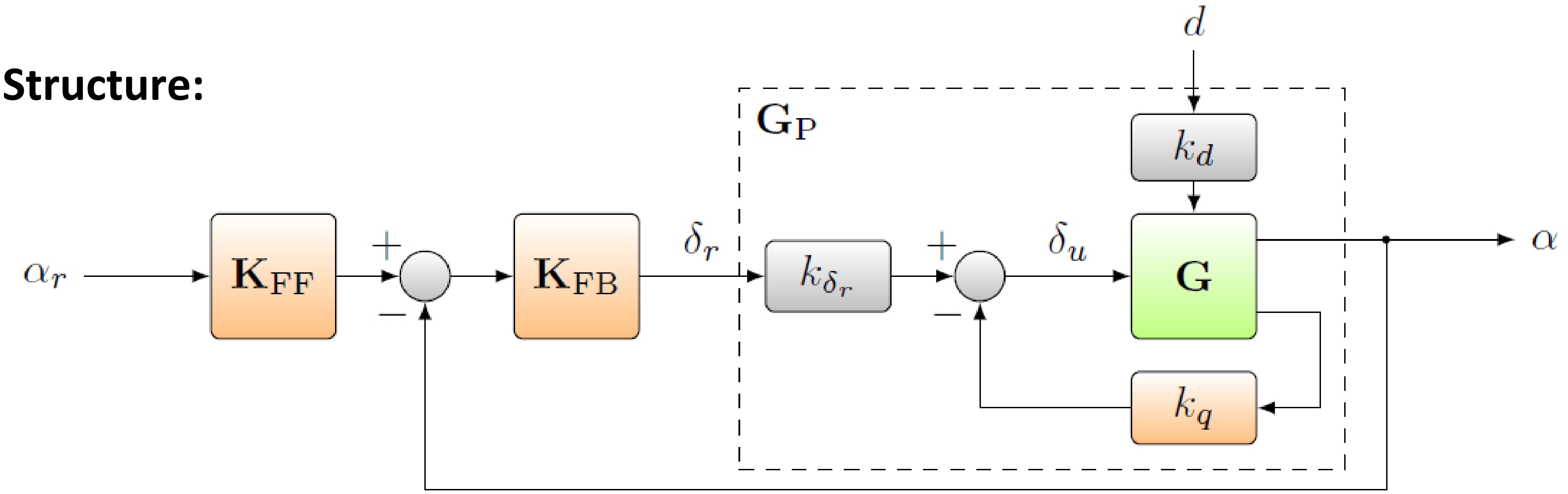
- **Remarks**
  - Good model fit with the validation data
  - Overall good confidence in the estimates,
  - Higher uncertainty for the M_{qq} parameter, and low α_{Trim}
  - Moderate parameter deviation
- **Nominal synthesis model from mean parameter values**
  - Multiplicative uncertainty takes into account observed deviations

Autopilot Design

- **Objectives**
  - Platform stabilization, reference tracking and disturbance rejection
  - Stability in presence of uncertainty

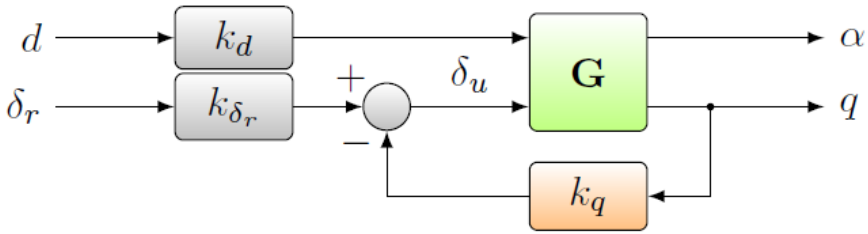
- **Design Requirements and Constraints**
  - Reference model: second-order low-pass filter with ξ=0.78 and ω_0=6 rad/s
  - Actuator bandwidth: 43 rad/s
  - Gain Margin (GM) > 6 dB, Phase Margin (PM) > 45°

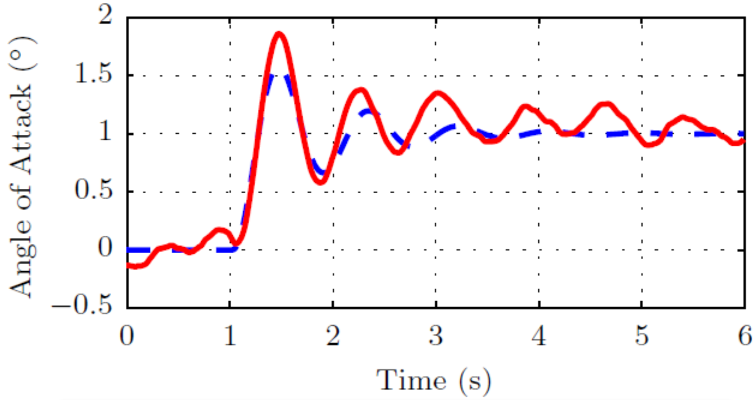
- **Structure:**



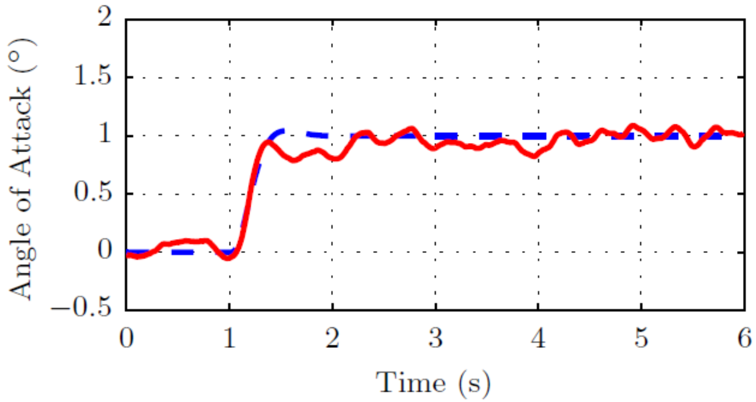
Rate Damping Controller

- **Improves the dynamic stability of the projectile**
  - Open-loop dominant pole damping: 0.17 (largely underdamped)
- **Virtually increase system damping with rate feedback**
  - kq selected such that the dominant pole damping is 0.7
- **Input scaling**





Open-loop response (k_q = 0)

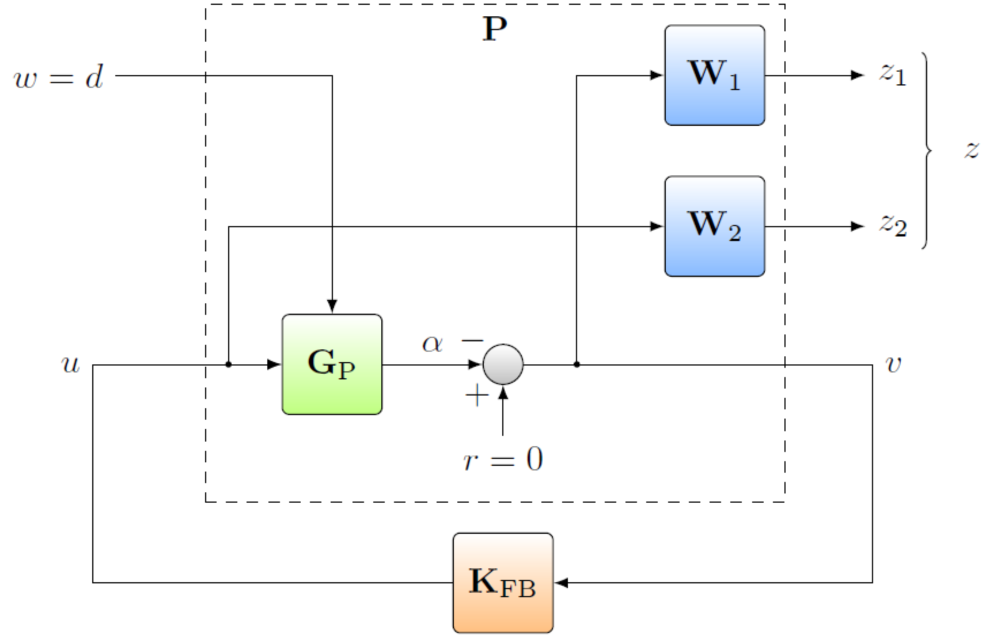


Damped response (k_q = 0.17)

Two-Step Controller Design

Disturbance rejection

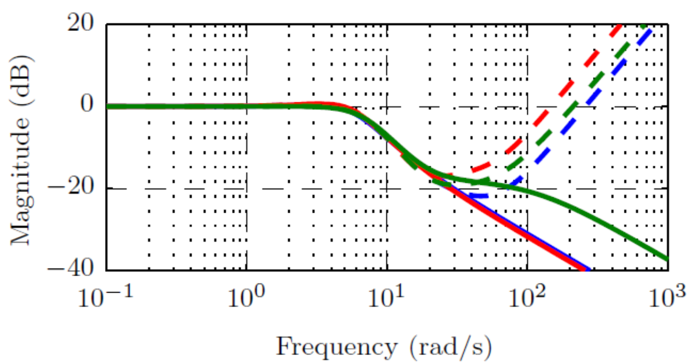
- **Mixed sensitivity H_∞ synthesis**
  - K_{FB} s.t. system is nominally stable and $\|T_{w\rightarrow z}\|_\infty < \gamma$
- **Sensitivity filter W_1**
  - Low sensitivity to disturbances at low frequencies
- **Control output filter W_2**
  - Limit high-frequency dynamics



Reference tracking

- **Inverse-based feedforward controller**

$$K_{FF} = T_{ref} \cdot T_{\delta_m \rightarrow \alpha}^{-1}$$



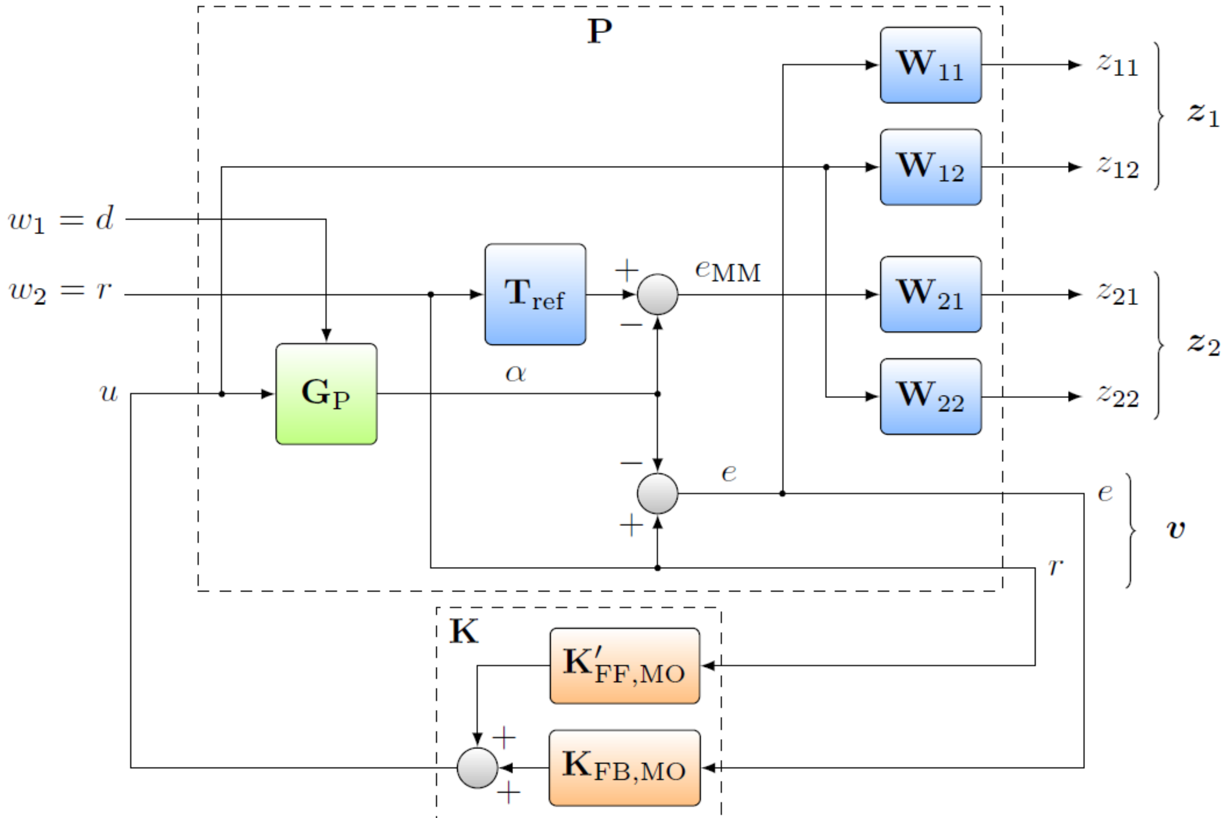
- **Non-proper, requires careful approximation**
- **Trade-off between complexity, tracking accuracy and high-frequency roll-off**

Multi-Objective H_∞ Synthesis

- **All constraints specified using performance filters**
  - W_{11} and W_{12} are identical to the previous case
  - W_{21} sets the admissible model-matching error
  - W_{22} limits high-frequency injection to the actuator

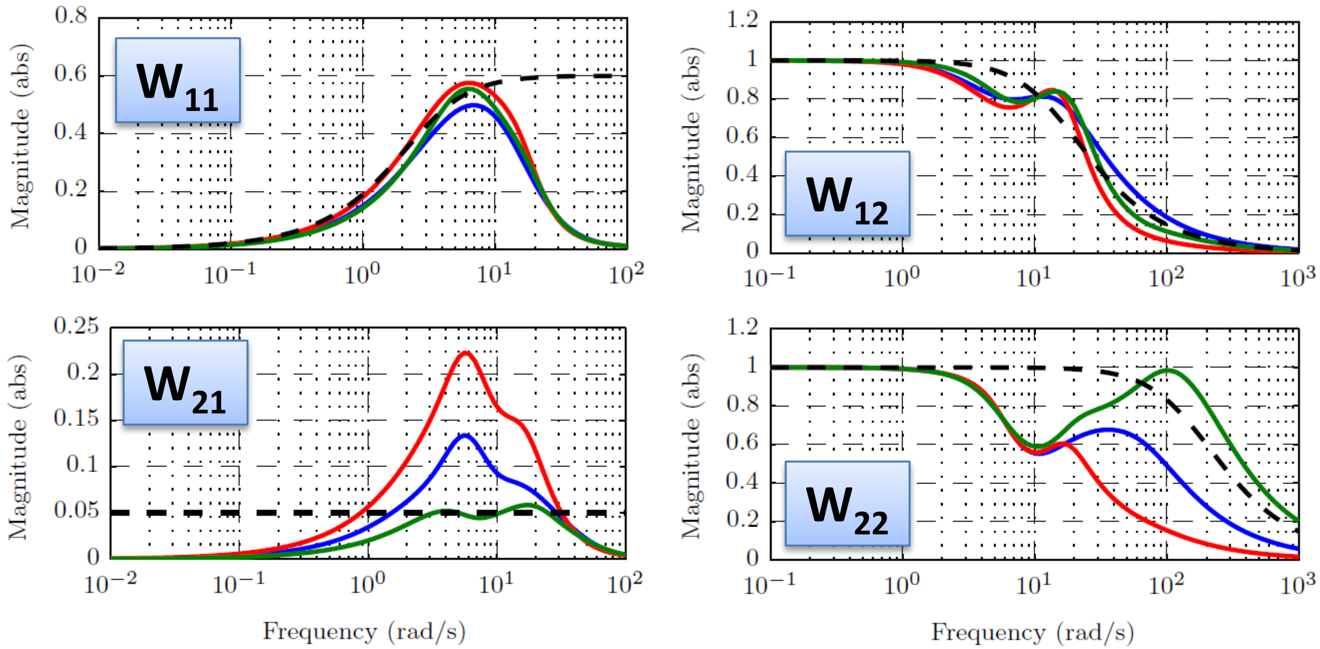
- **Controller K**
  - 2 DoF, fixed order and structure
  - Ensures stability
  - Satisfies:

$$\left\| \begin{Bmatrix} T_{w_1 \to z_1} \\ T_{w_2 \to z_2} \end{Bmatrix} \right\|_\infty < \gamma$$



Synthesis Results

- **Frequency-domain performance**



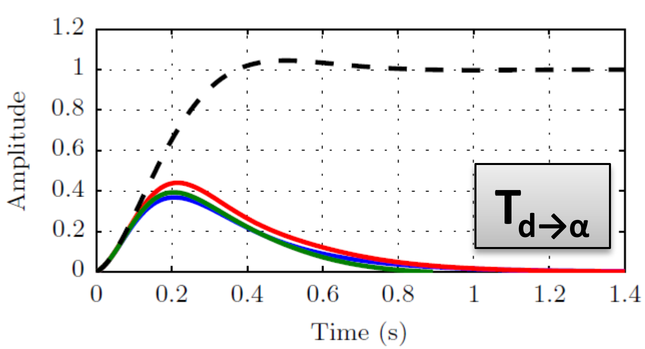
Fixed-order

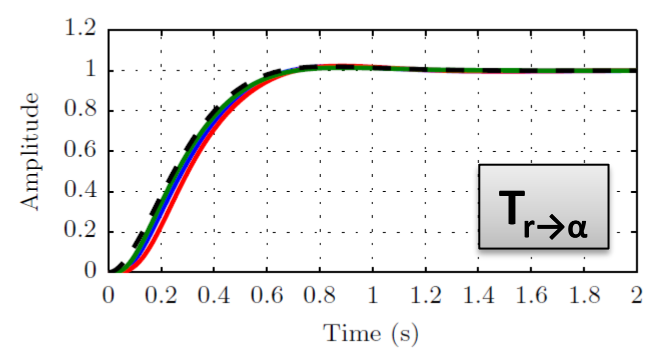
Full-order

Multi-objective

Weighting filter

- **Time-domain performance**



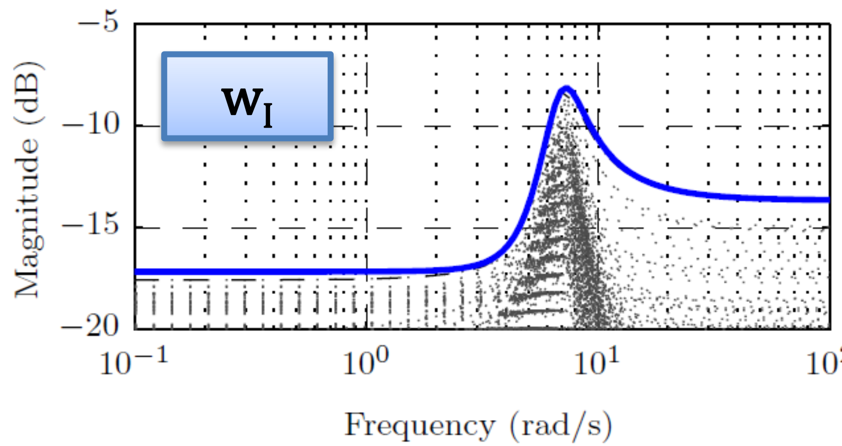


Robustness Analysis

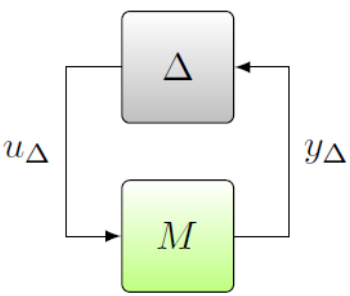
- **Uncertainty modeling**
  - Multiplicative input uncertainty

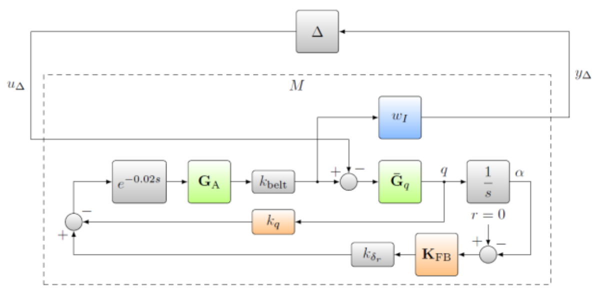
$$\mathbf{G}_q(s) = \mathbf{G}_q(s)\left(1 + w_I(s)\Delta_I(s)\right)$$

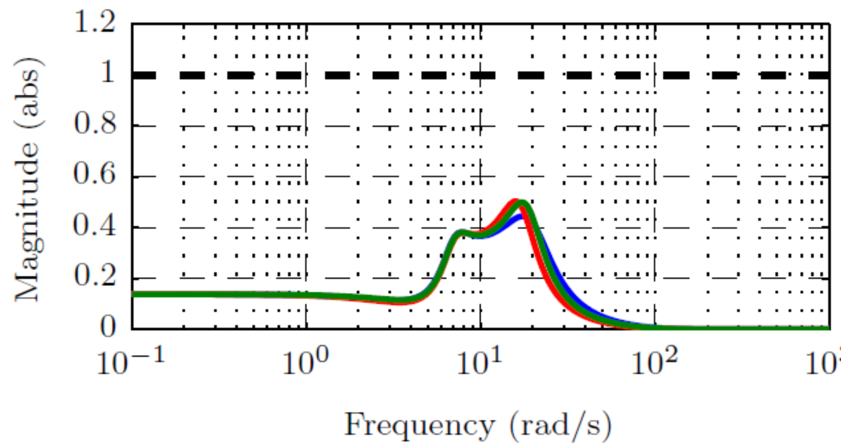
  - w_I bounds all relative error transfers



- **Robust Stability**
  - M-Delta representation





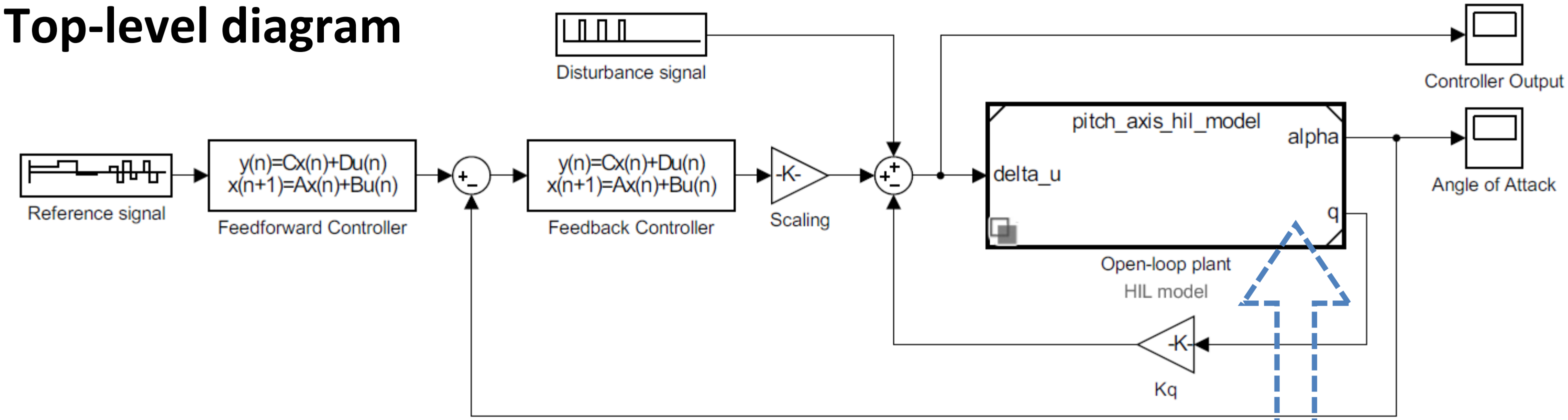


  - Stability condition

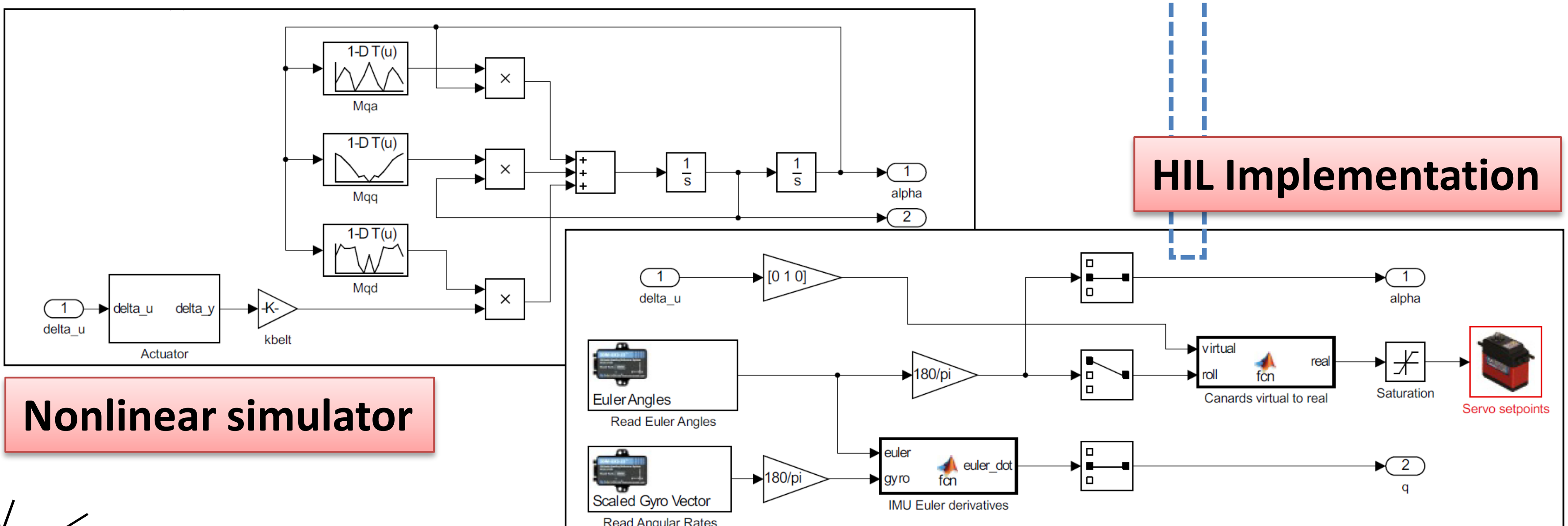
$$|M(j\omega)| < 1, \forall\omega$$

Controller Implementation

- **Top-level diagram**

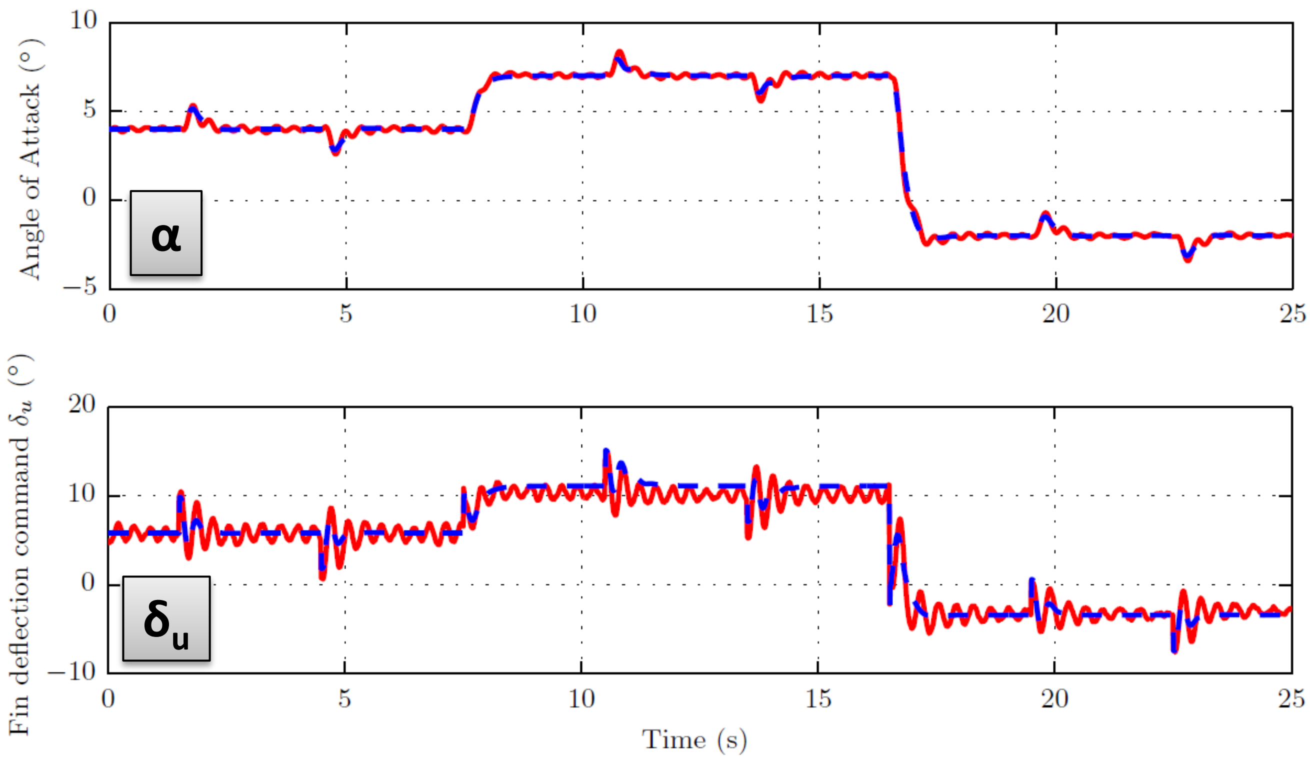


- **Referenced model**



Controller Validation: Disturbance Rejection

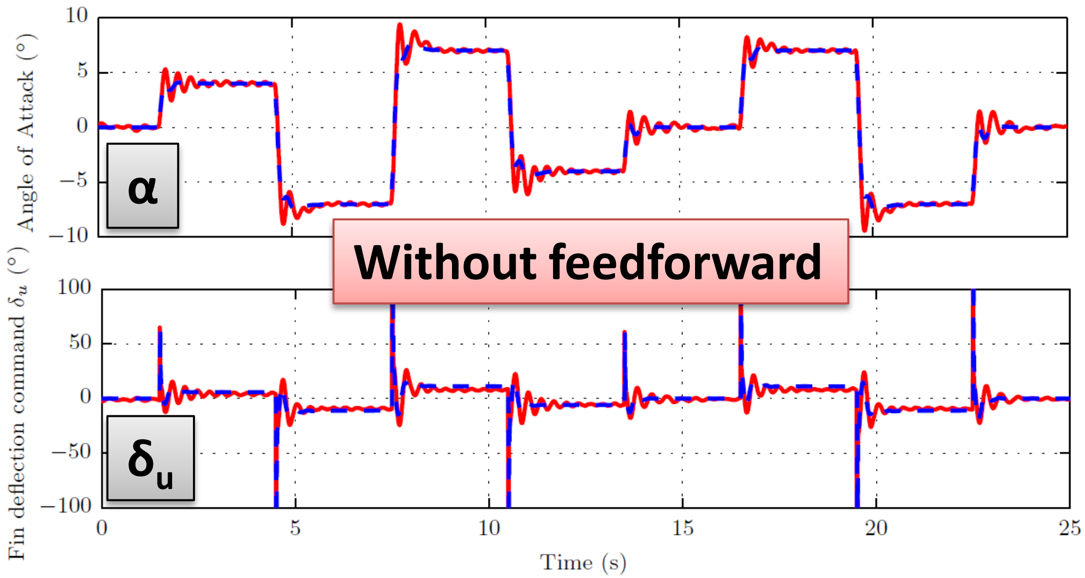
- **Simulated disturbance at plant input**
  - 4° amplitude steps

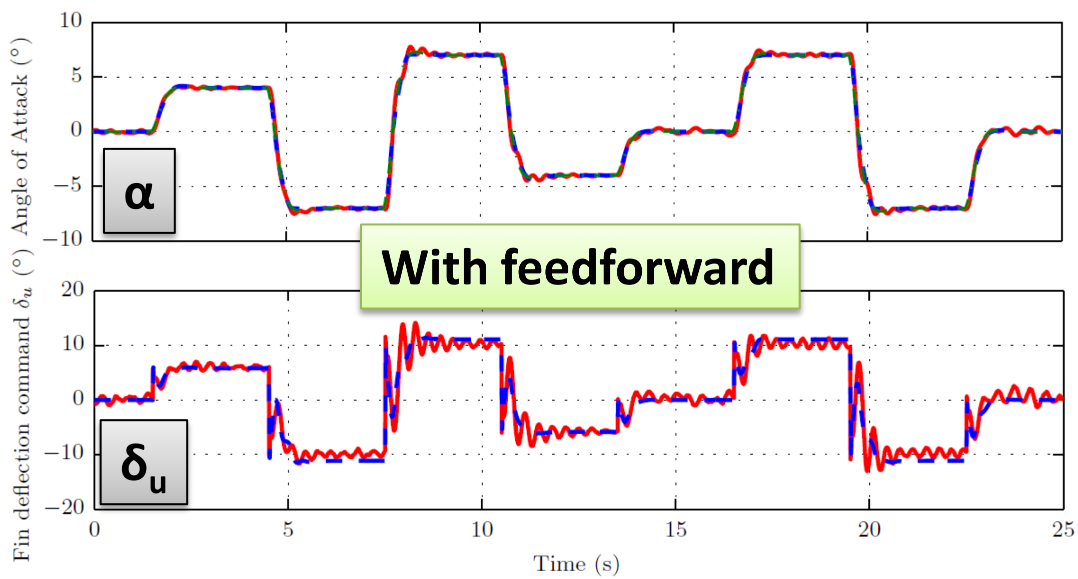


- **Results:**
  - > 60% attenuation,
  - < 1 s response time

Controller Validation: Reference Tracking

- **Large-scale reference steps**
- **Importance of the feedforward filter**
  - Limits actuator signal peaking at reference signal discontinuities
- **Results (with feedforward)**
  - 800 ms 2% response
  - No steady-state error
  - Limited actuator peaking

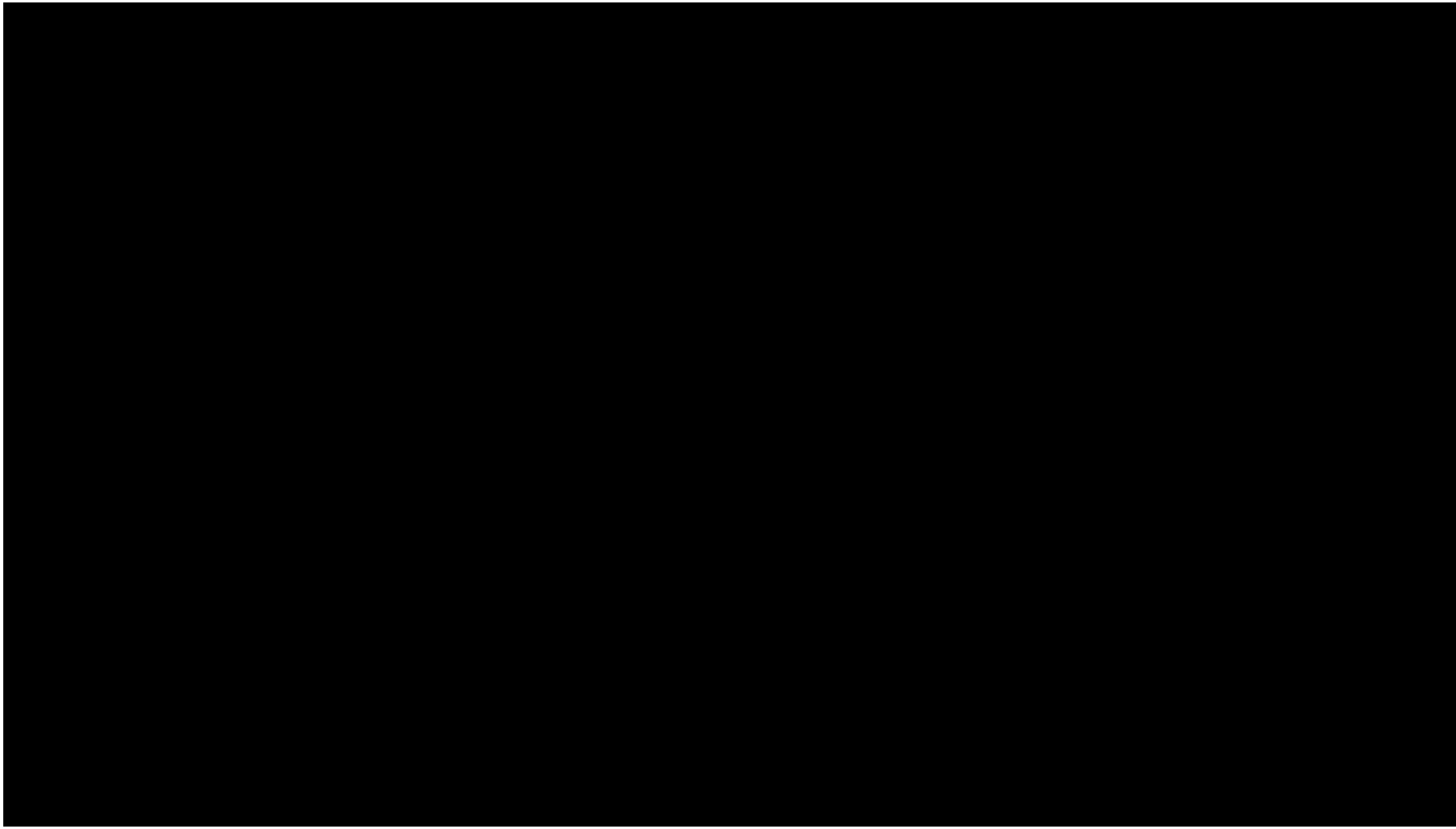




HIL Results

Simulation

Video



Conclusion

- **Pitch axis autopilot design for the ACHILES projectile prototype**
  - Nominal model from mean value of estimated parameters
  - Disturbance rejection and reference tracking objectives
  - Two-step approach and multi-objective synthesis lead to similar results
  - Very good agreement between simulation and experimental results

- **Roadmap**
  - Extension to the yaw axis
  - Coupled pitch + yaw identification and control
  - Varying airspeed

Thank you for your attention !