Envelope Protection and Autopilot Overview

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The Group

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SMART ICING SYSTEMS
Research Organization

Core Technologies

- Aerodynamics and Propulsion
- Flight Mechanics
- Control and Sensor Integration
- Human Factors/ Cognitive Engineering
- Aircraft Icing Technology

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IMS Functions

- Characterize Icing Effects
- Operate and Monitor IPS
- Envelope Protection
- Adaptive Control

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Systems Integration

- Flight Simulation
- Flight Test

Related Work

- W. Li, “Parameter Identification for Smart Ice Management Systems,” MS thesis, Dept. of AAE, UIUC, May 1999
- V. Sharma and P. G. Voulgaris, “Effects of Icing on Autopilot Performance,” AIAA Paper 2002-0815, Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 2002
- K. N. Hossain, M. B. Bragg, V. Sharma, P. G. Voulgaris, “Envelope Protection and Control Adaptation in Icing encounters,” to be presented at the AIAA conference in Reno, NV, Jan. 2003
- Vikrant Sharma, “Twin-Otter Autopilot analysis, design and envelope protection schemes for operation in icing conditions,” MS thesis, Dept. of AAE, UIUC, September 2002

Objectives

- Develop and analyze envelope protection techniques for operation in icing conditions

- Investigate standard autopilot behavior in icing conditions

- Investigate alternative autopilot schemes for operation in icing conditions

Approach

- Prediction-based, dynamic, envelope protection without autopilot operation

- Prediction based, dynamic, envelope protection with autopilot operation

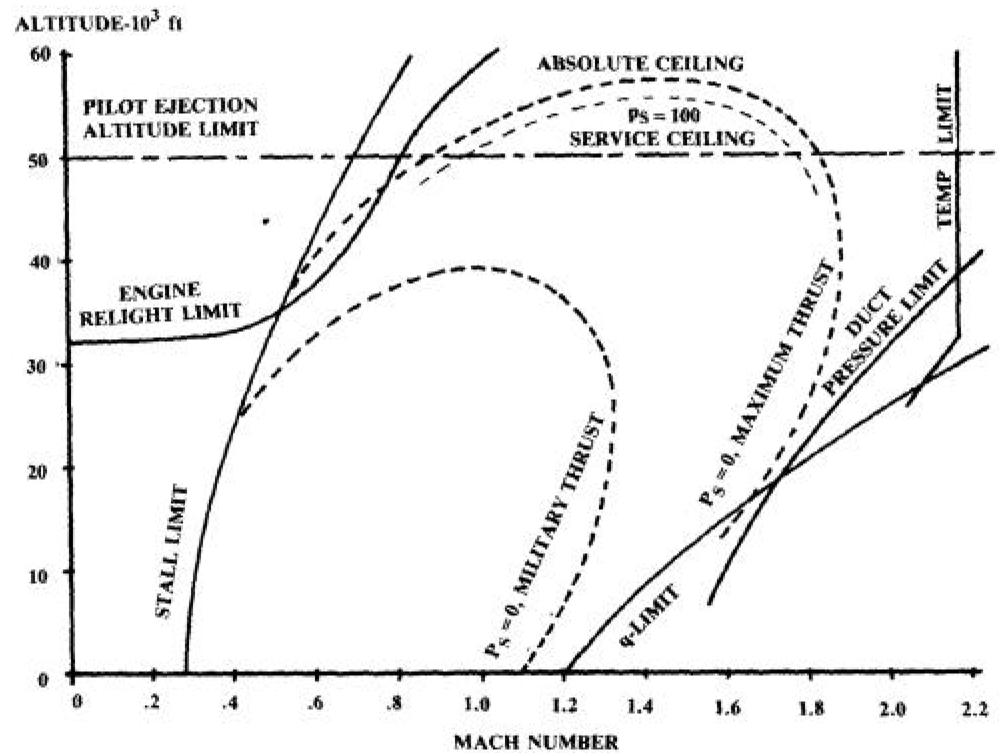
- A/P stability and performance characterization using robust control techniques

Outline

- Envelope protection without autopilot operation
- Envelope protection with autopilot operation
- A/P modes and structures
- Work in progress-Future research

Typical Flight Envelope

- Aerodynamic Limits
- Thrust/Power Limits
- Structural Limits
- The flight envelope is primarily a function of load factor, velocity and altitude
- The clean aircraft flight envelope remains constant



Example of a Clean Aircraft Flight Envelope from Ramer 1989.

Envelope Protection for Commercial Jets

- Fly-by-wire system
- Pre-set limits
- Feel actuators
- Bank angle protection
- Stall protection
- Boeing: soft limits on control surface deflections
- Airbus: hard limits on the aircraft aerodynamic angles

ATR 72

Stall Protection

- Aural warning and stick shaker at $\alpha = 18.1^{o}$
- Stick Pusher at an angle closer to stall
- If IPS in level II, α for stick shaker is reduced to 11.2^{o} in cruise
- α for stick pusher reduced as well

The Dynamic Envelope

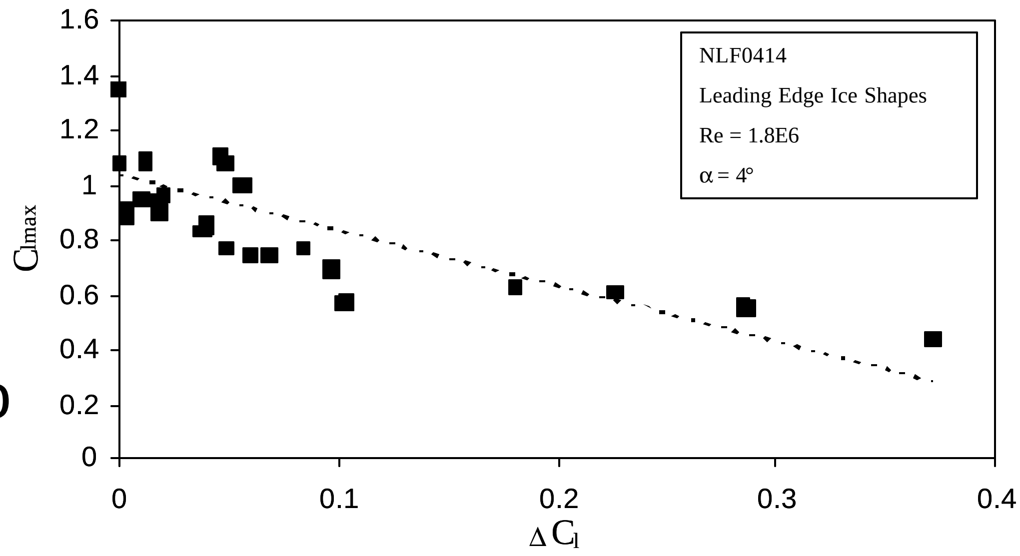
- Typically there are pre-set limit values
- **Problem** - Limits change with level of ice accretion.
- **Solution** - In icing conditions the limits have to be determined and enforced dynamically during flight.

Critical Parameters

- The critical parameters:
  - α_w : Wing angle of attack
  - α_t : Tail angle of attack
  - ϕ : Roll angle
- Limits can be defined for these parameters as a function of ice accretion.

Angle of Attack Limiting

- C_{lmax} vs ΔC_l fitted as linear functions for several AOA.
  $$C_{L_{\max}} = f(\Delta C_L(\boldsymbol{h}_{ice}, \boldsymbol{a}))$$
- The trim AOA used to find corresponding fit.
- The AOA corresponding to the C_{lmax} is then set as the limit



Current System Limitations

Typically sensor data are used to cue the pilot or drive the flight control system.

- **Problems**: Limits may easily be exceeded since only current values are sensed and the sensor data may not be very effective for rapid changes.
- **Solution**: System needed for prediction of future values from available sensor data including control positions.

Our EP Approach

- Implement and test a '0th order' EP scheme: if $\alpha > \alpha_{max}$ generate warning

- Develop more sophisticated schemes based on prediction

- Two modes: A/P on, A/P off

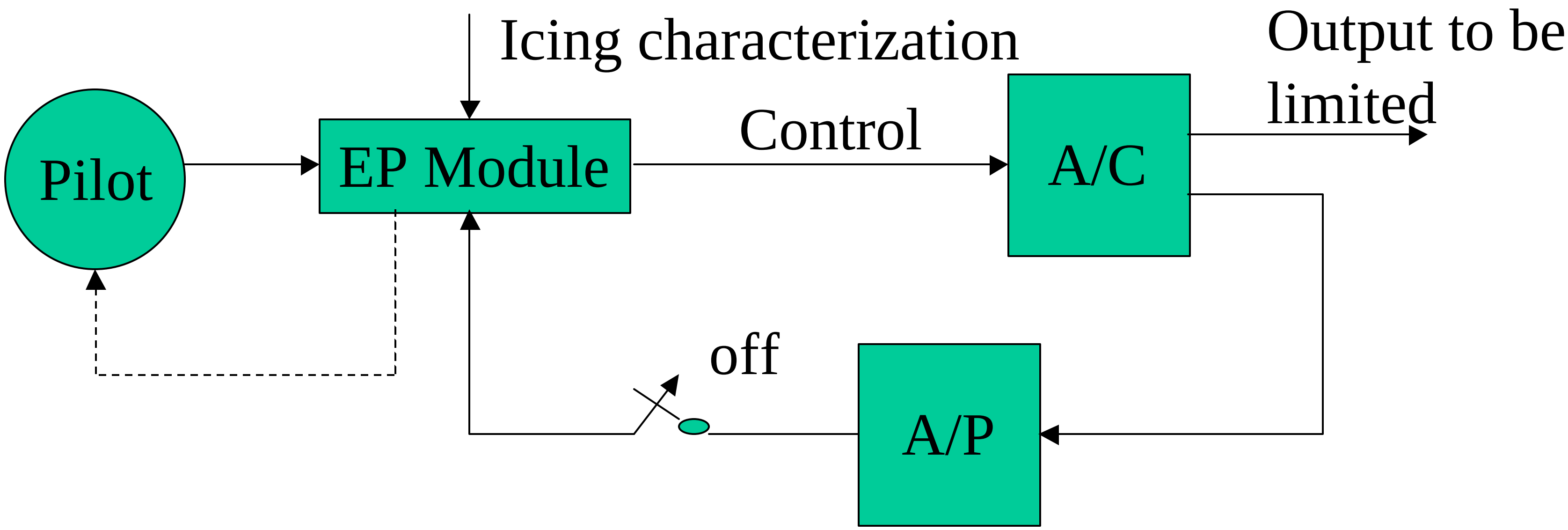
Why two EP schemes

- Current guidelines suggest A/P off under icing $\Rightarrow$ ‘open loop’ EP necessary

- Future planes will rely heavily on automation $\Rightarrow$ ‘closed loop’ EP is essential

EP with A/P off

- Pilot stick positions correspond to fixed position of control surfaces
- EP module continuously calculates limits on stick position and informs pilot

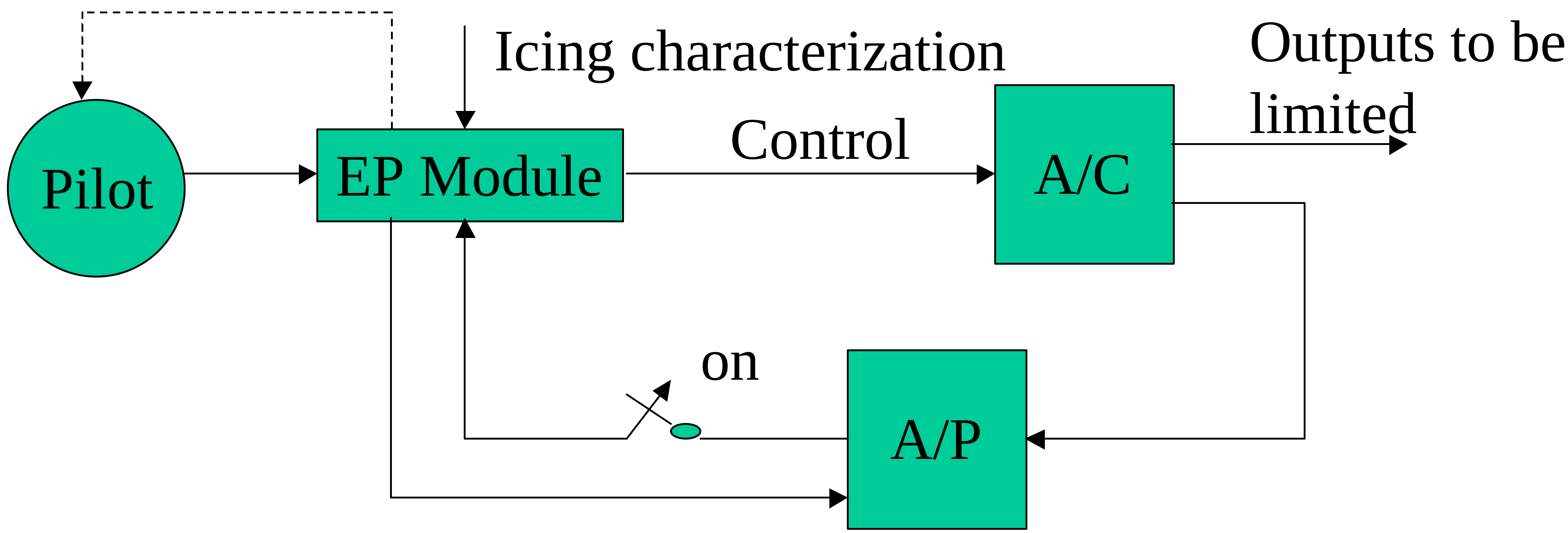


Open Loop EP

- Monitor A/C dynamic state and icing level
- Predict on-line future A/C state with current control inputs
- Warn pilot based on prediction

EP with A/P on

- Pilot stick position dynamically affects control position
- EP continuously calculates limits on stick position and informs A/P



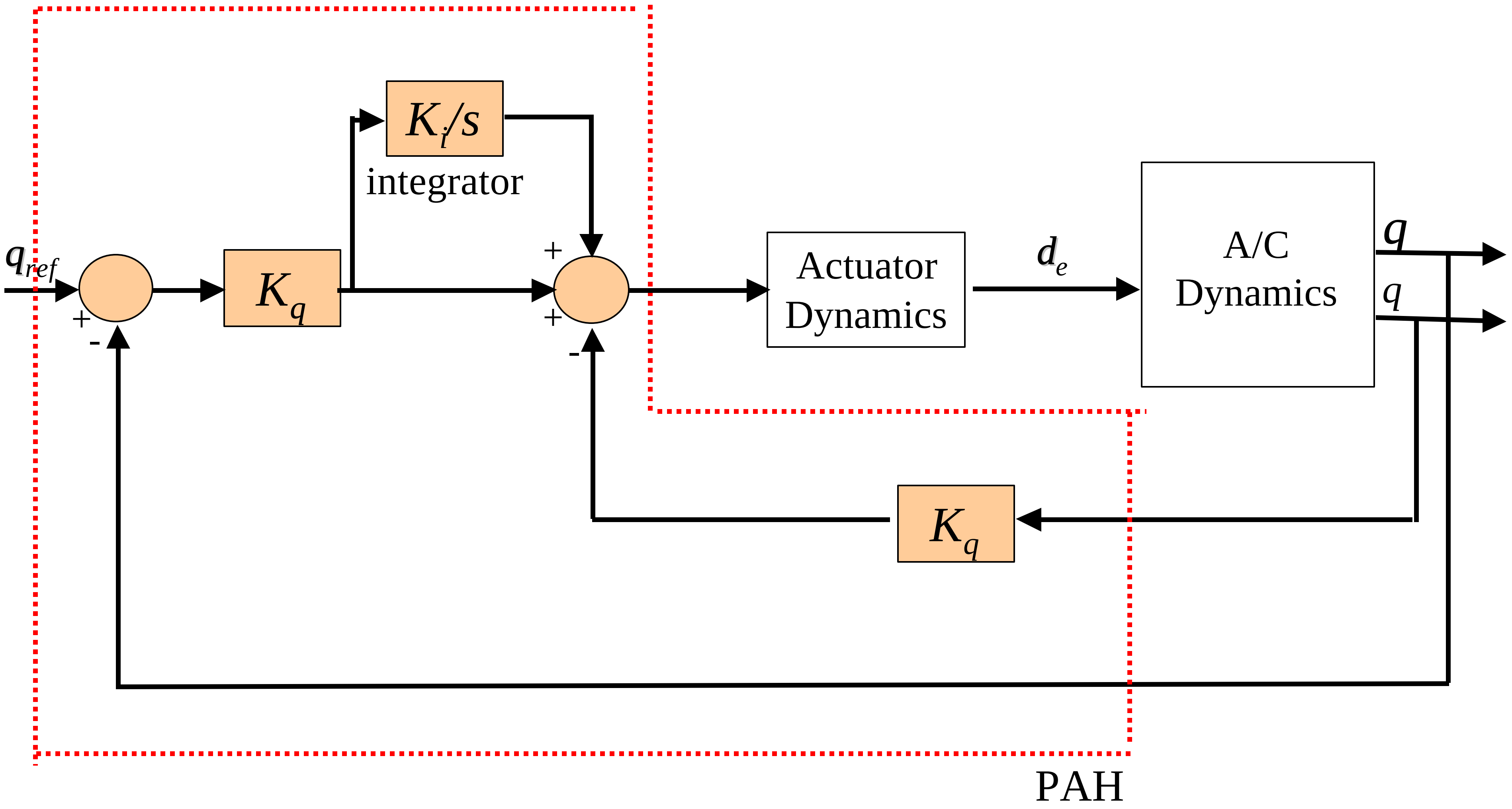
Closed Loop EP

- Monitor A/C state, A/P state and icing level
- Predict on-line future A/C state with current pilot input
- Adjust input based on prediction, inform pilot
- Same principle as open loop; different dynamical equations

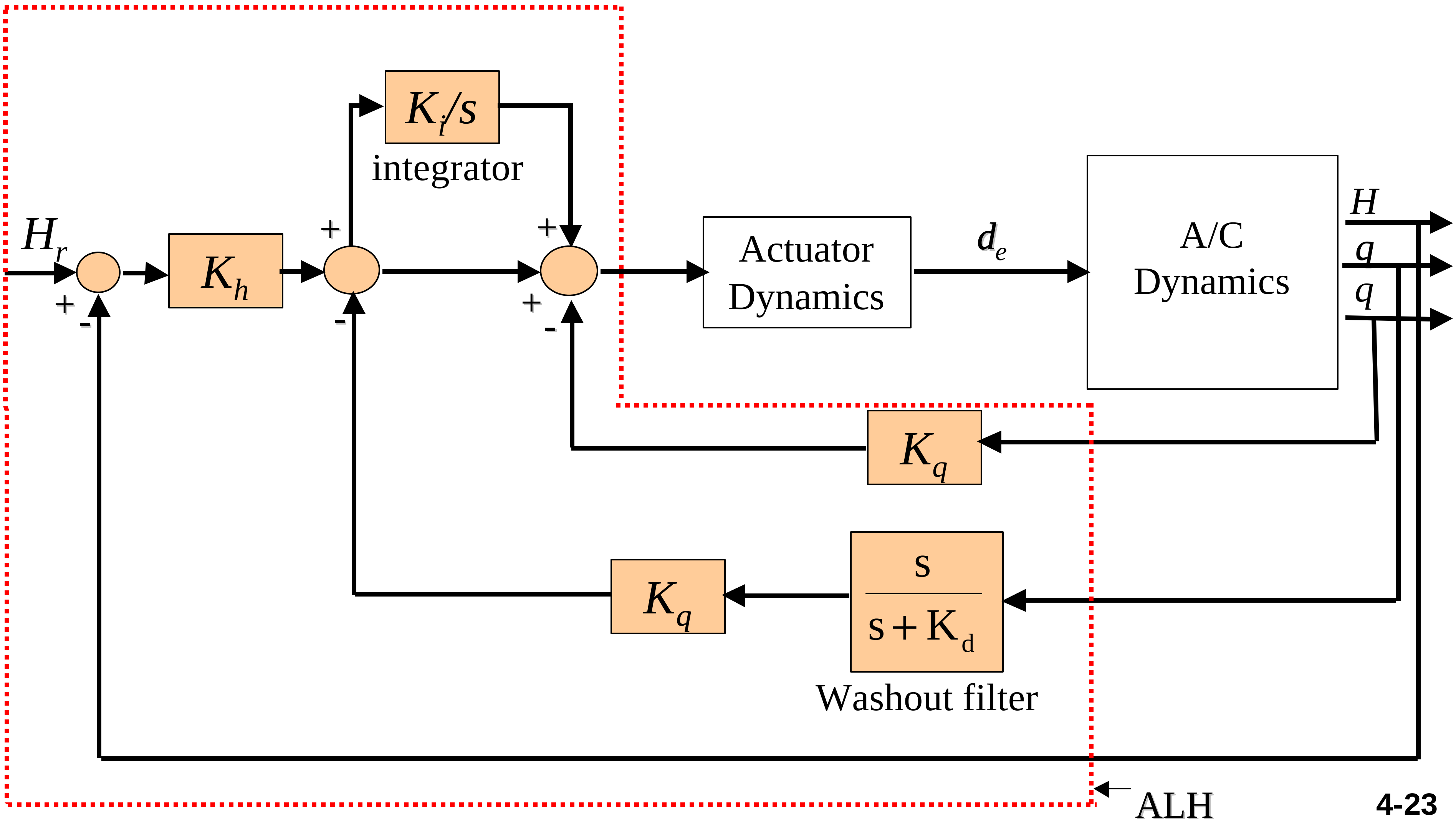
Autopilots

- **Longitudinal Modes**
  - Pitch Attitude Hold (PAH)
  - Altitude Hold (ALH)
- **Lateral Modes**
  - Roll Attitude Hold (RAH)
  - Heading Hold (HH)

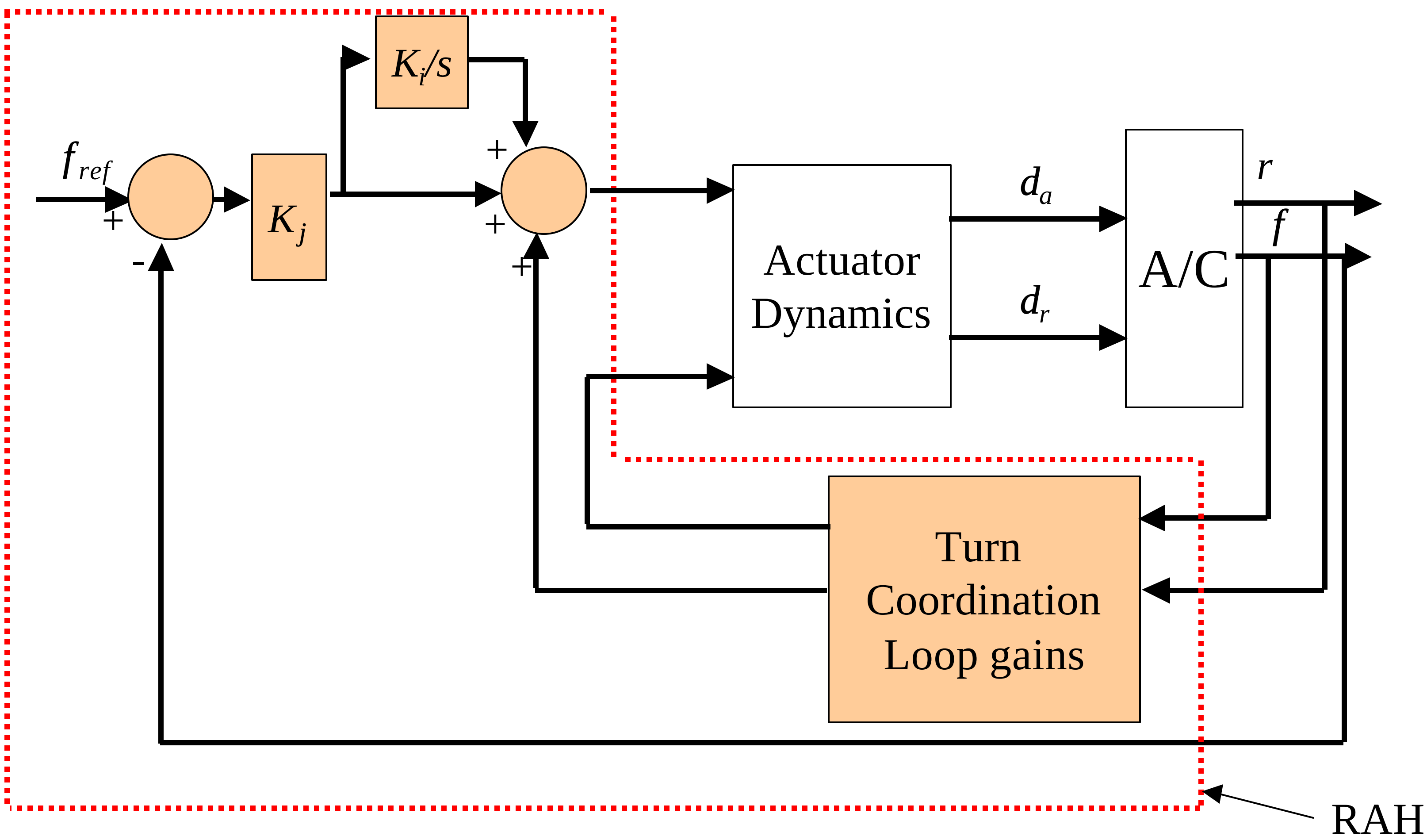
Block Diagram for PAH



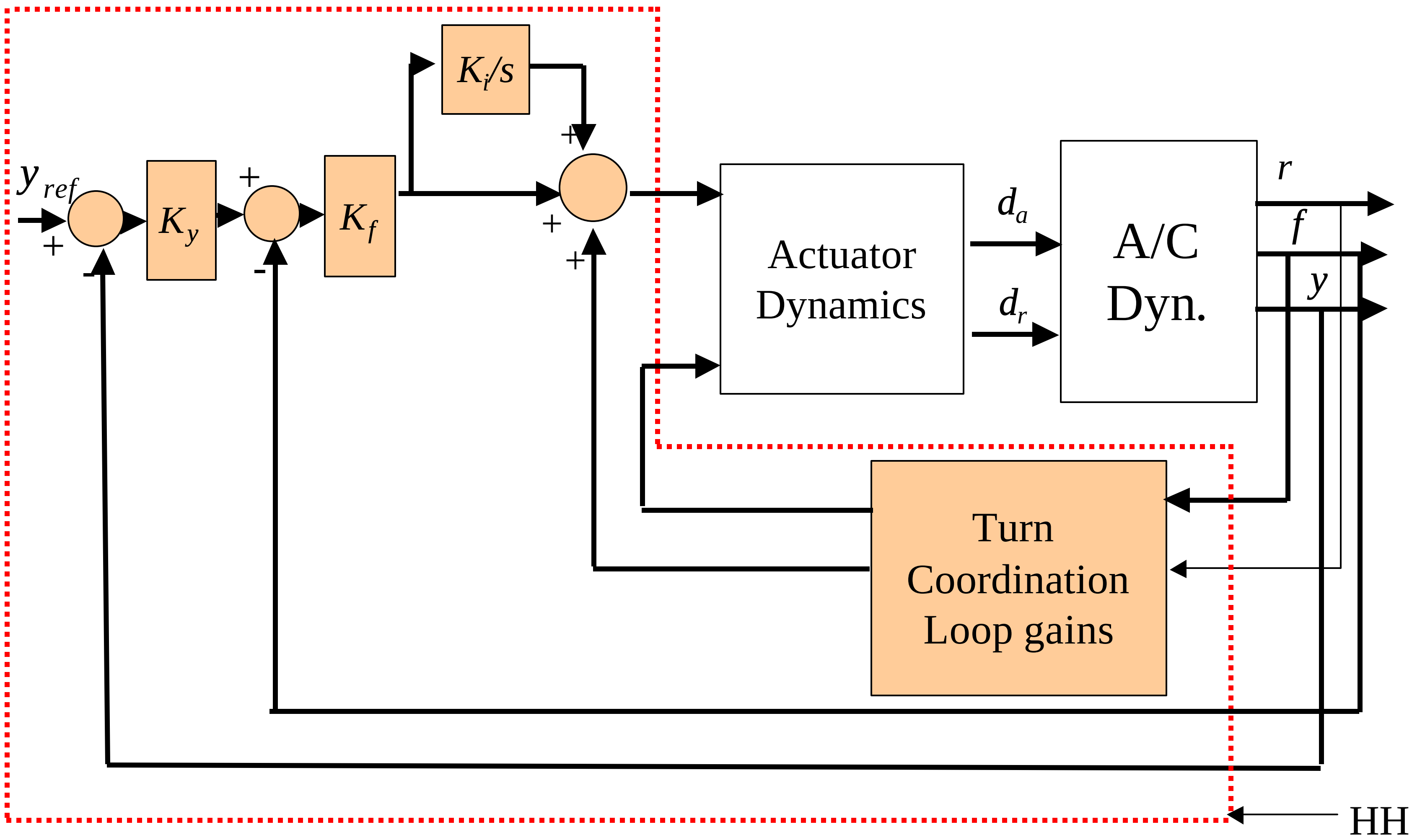
Block Diagram for ALH



Block Diagram for RAH



Heading Hold



A/P Performance

- Gains are scheduled on A/C speed
- Local designs exhibit good performance and stability margin properties
- Overall A/P performs well over the operational envelope of Twin Otter for clean conditions
- PAH performs well under icing conditions in the linear regime.

Work in Progress

- Complete development of advanced EP modules (OL and CL)
- Test on nonlinear simulator
- Coordinate with Human Factors
- Complete study on alternative PAH A/P designs

Recommendations for Future Research

- Full scale development of prediction-based EP modules to include all envelope-critical variables: lateral variables, control deflections, power, etc.
- Full scale PAH, ALH, RAH, HH assessment of standard A/P behavior in icing conditions
- Alternative A/P designs based on advanced methods that feature A/P adaptation for upset recovery and proof of safety, handling of failures in control surfaces, etc.