IEEE Santa Clara Valley

Control Systems Society Technical Meeting

September 21, 2000

Flight Control System Design and Test for Unmanned Rotorcraft

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Overview

- Background
- Design Tools
- Design Methods
- UAV programs
- Example

Background

- A UAV is an uninhabited, reusable aircraft that is controlled:
  - Remotely,
  - Autonomously by pre-programmed on-board equipment,
  - Or a combination of both methods
- Currently >241 UAV systems developed by 31 countries are operational or in test
- Numerous missions, current and proposed:
  - Military
  - Civilian
  - Space

Source: Bob Keith, NATO UAV C2 Workshop 1999 (Unclassified).

Background

Background

- Many vehicle configurations, but rotary-winged vehicles form a significant and growing portion

- Hover-capable UAVs offer unique capabilities, but come with unique challenges

Background

- Significant industrial and military expertise exists in fixed-wing UAV development.

- Initial work on rotary-wing UAVs did not exploit the capabilities of the configuration:
  - Lack of familiarity with rotorcraft issues
  - Inability to foresee problem areas

- NASA involvement in rotorcraft UAV development sought to take performance to a new level.

Background

- Ames is NASA rotorcraft center:
  - Army / NASA Rotorcraft Division
    - NASA: Aerospace Directorate
    - Army: Aviation & Missile RD&E Center
  - Flight Control and Cockpit Integration Branch
- Expertise in rotorcraft:
  - Flight control
  - Modeling
  - Simulation
- Design tools developed in-house

Design Tools

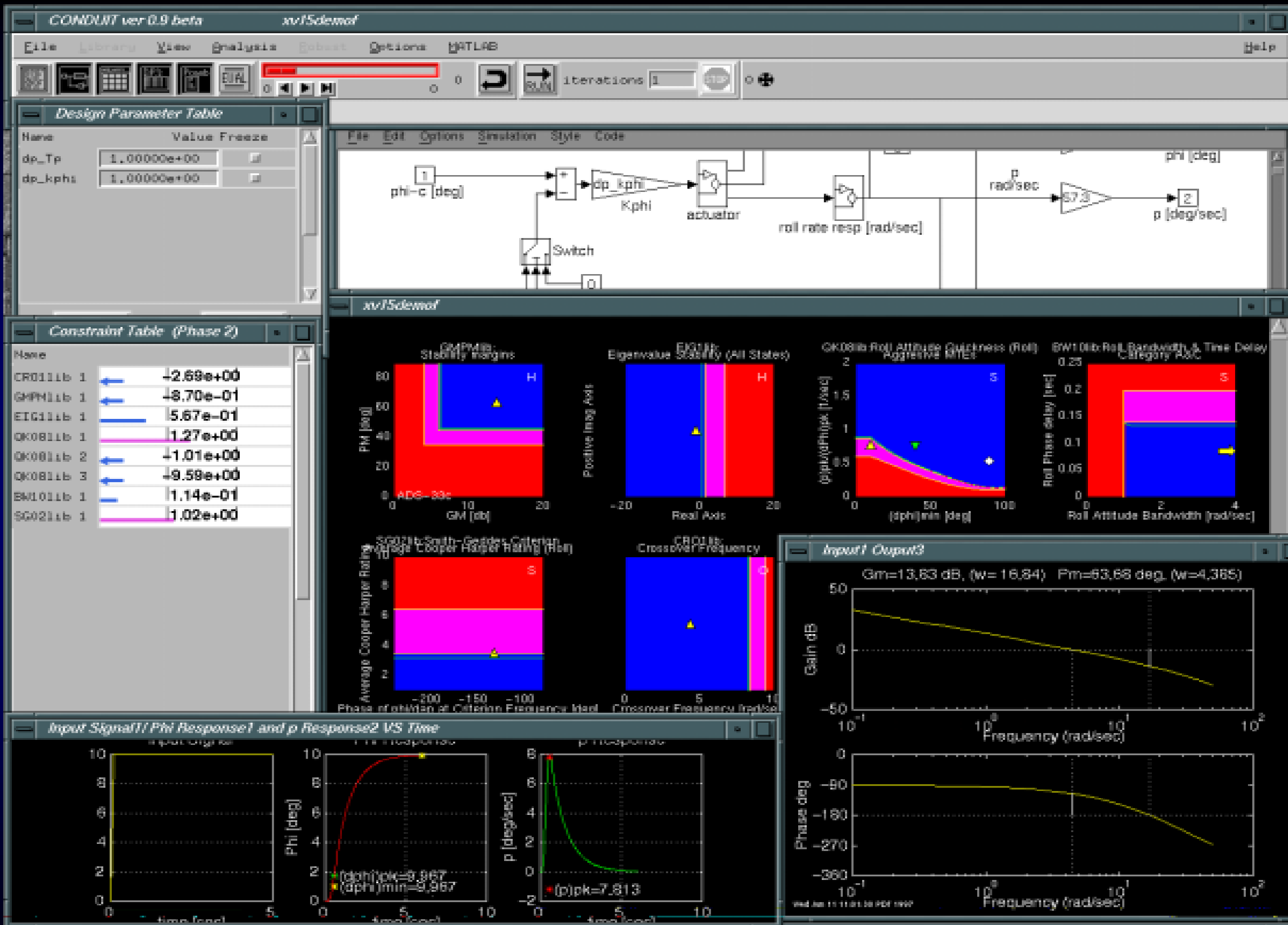
- CIFER®
  - Comprehensive Identification from Frequency Responses
- CONDUIT
  - CONtrol Designer's Unified InTerface
- RIPTIDE
  - Real-time Interactive Prototype Technology Integration/Development Environment

Design Tools

- CIFER®
  - Extraction of mathematical description of vehicle dynamics from test data
  - “Inverse” of simulation
  - Robust software, widely used in aerospace industry

Design Tools

- CONDUIT
  - Evaluation and analysis of any modeled system
    - Linear model from CIFER
    - Non-linear simulation code
  - Control system design
    - Simulink or SystemBuild block-diagram modeling
  - Control system optimization
    - User-selected specifications
    - Multi-variable, multi-objective FSQP



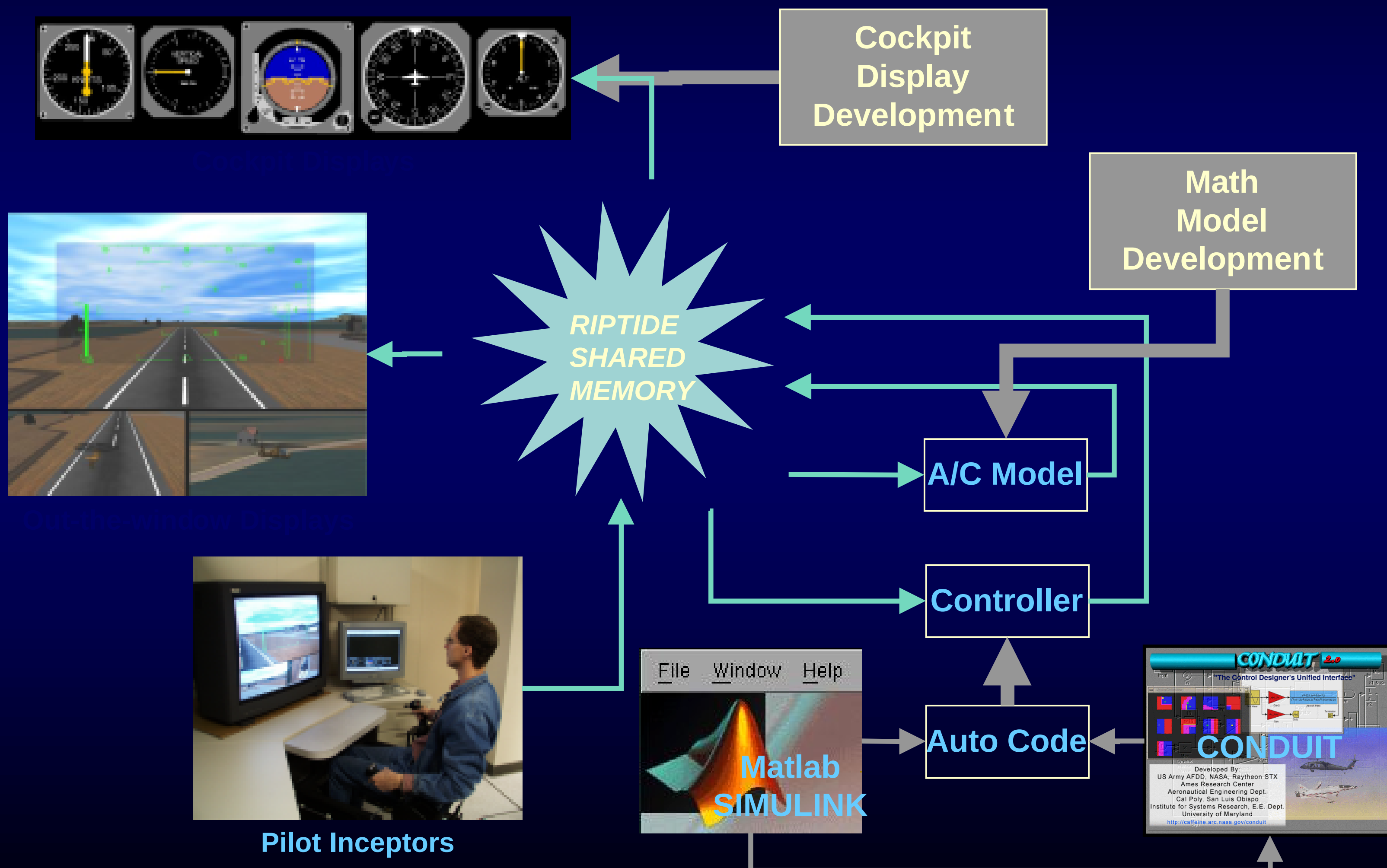
UAV Control Design

Design Tools

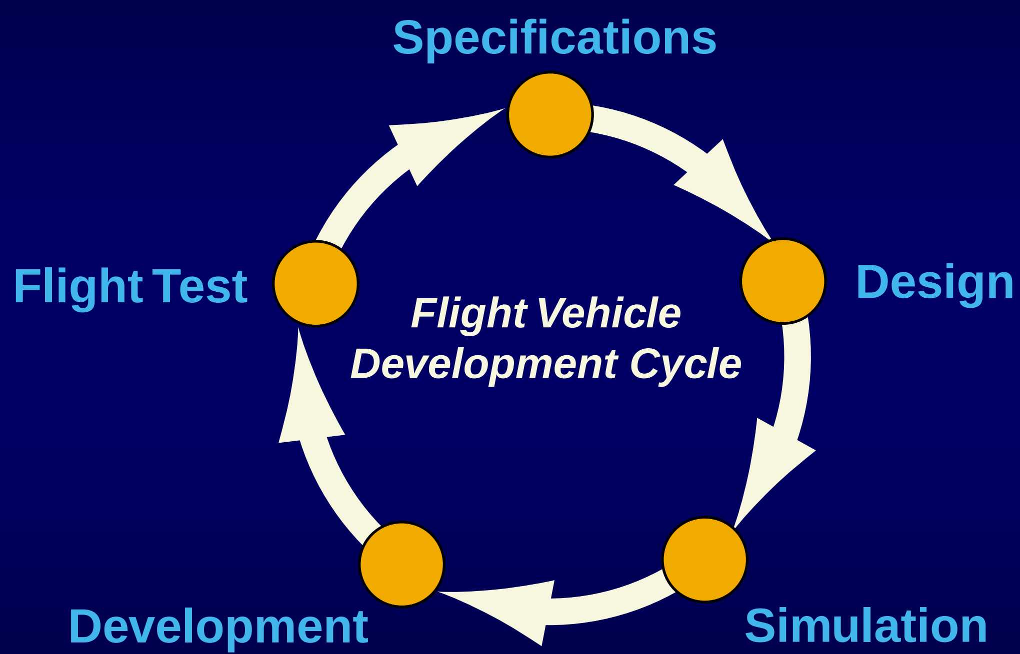
- RIPTIDE
  - Real-time simulation environment
  - Can use models from CIFER, CONDUIT, or stand-alone code
  - Can use control system designs from CONDUIT
  - Hardware-in-the-loop capability

Design Tools

Elements of RIPTIDE real-time simulation environment



Design Methods



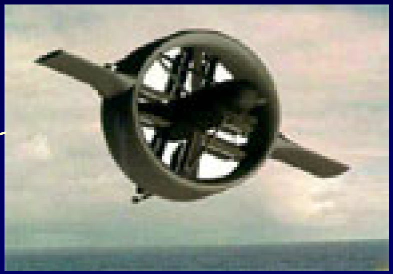
Design Methods

- Typical sequence of control system development:
  - Collect data from vehicle
  - Extract linear math model using CIFER
  - Design control system using CONDUIT
  - Optimize control system gains using CONDUIT
  - Shakedown tests in RIPTIDE
  - Fly control system on vehicle
    - If modeling done correctly, vehicle response should match model predictions.

UAV Programs

Ames participation in:

- VTUAV
- LADF
- R-50/R-MAX
- BURRO



Example: BURRO

- USMC demonstration program
- **B**road-area
  Unmanned
  Responsive
  Re-supply
  Operations
- UAV to pick up loads from moving ship, deliver autonomously to inland troops

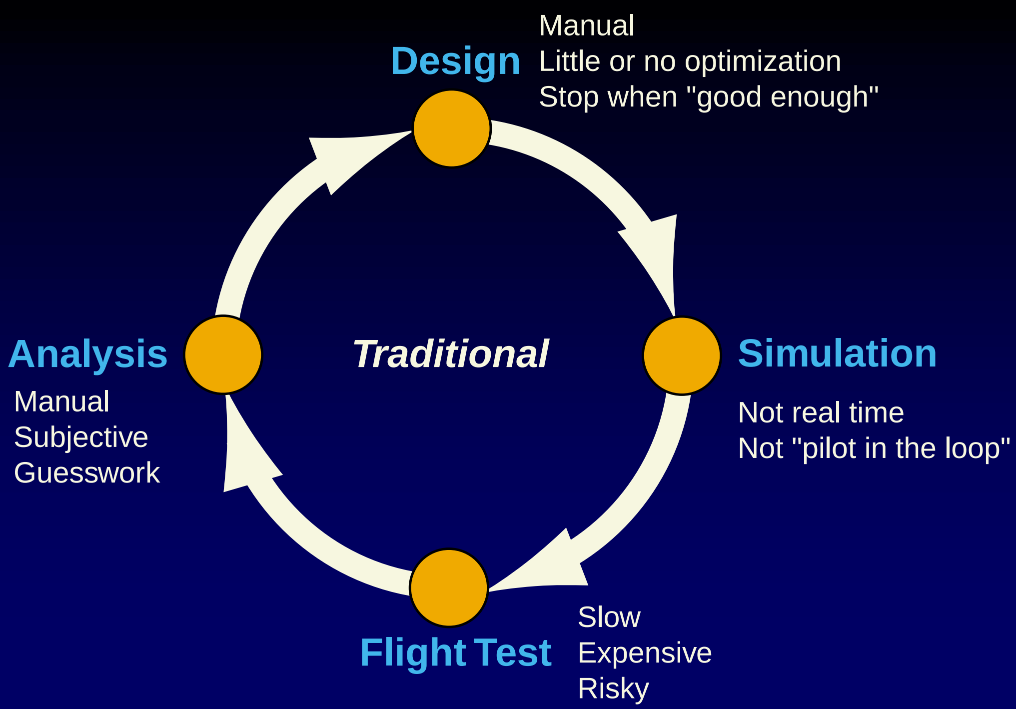
Introduction

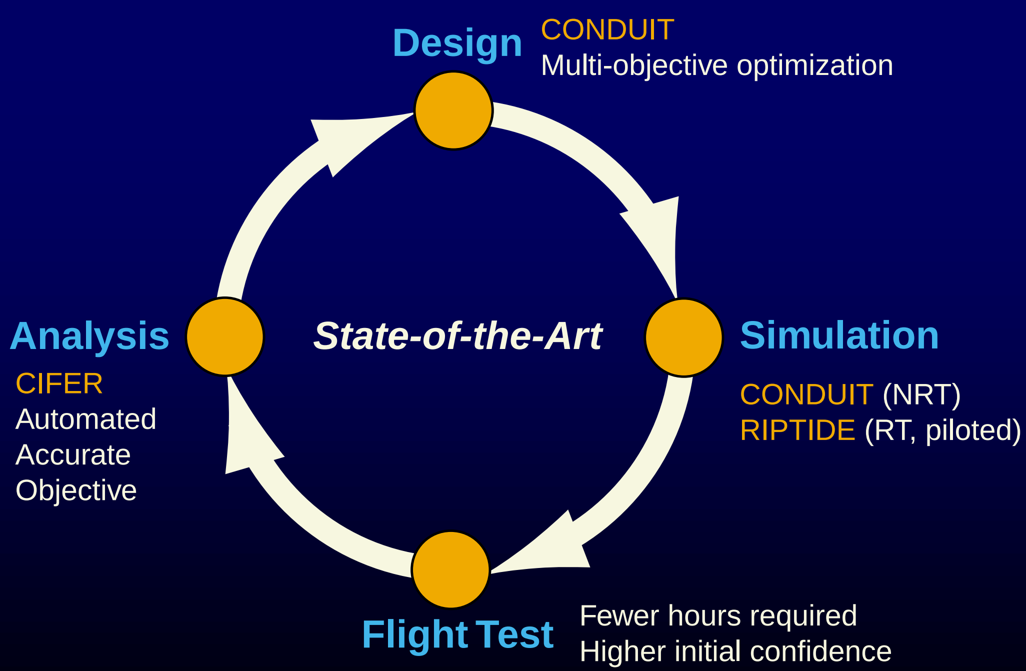
- Kaman Aerospace K-MAX
  - In production
  - Designed for load-lifting
  - 6,000 lb vehicle
  - 6,000 lb slung load capacity
  - Synchropter configuration
  - Servo-flap rotor

Introduction

- Army/NASA CRDA with Kaman to support FCS development
- Three integrated tools
  - CIFER® : System identification
  - CONDUIT: Control system modeling, analysis, optimization
  - RIPTIDE: Desktop real-time simulation

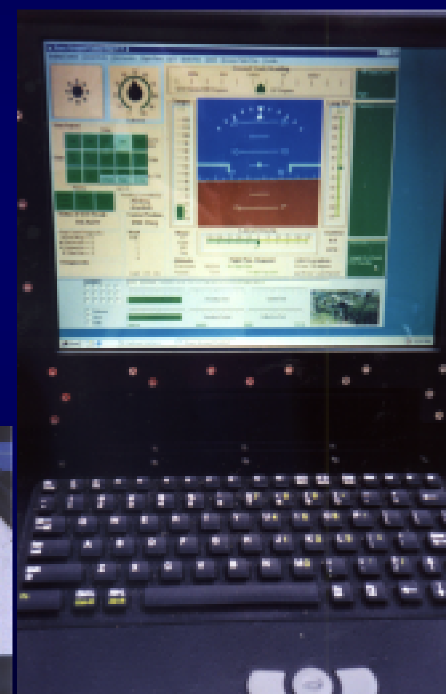
Introduction

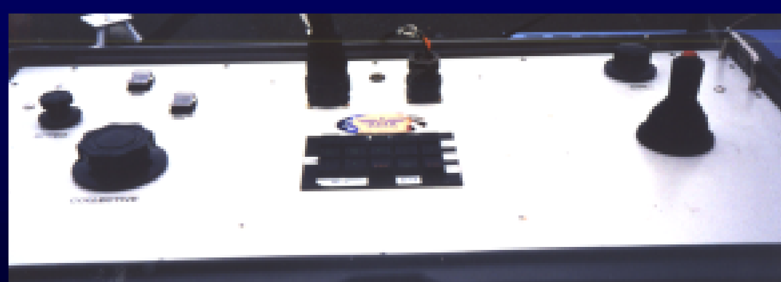




Introduction

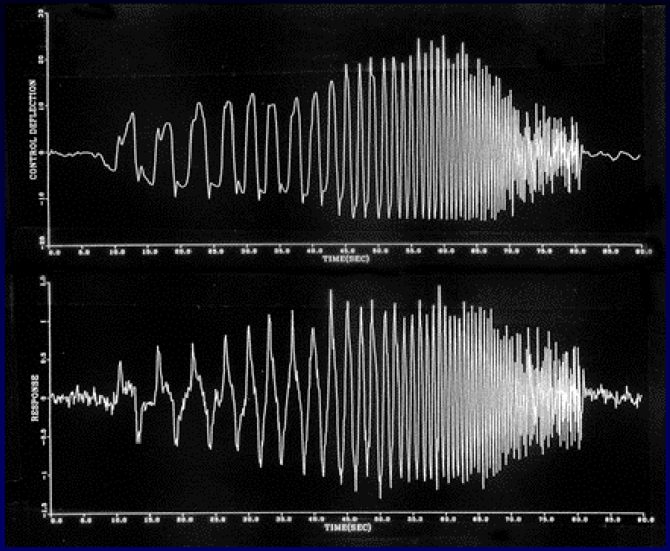
- Scope:
  - Hover / low-speed
  - Unloaded
  - Ground operator control

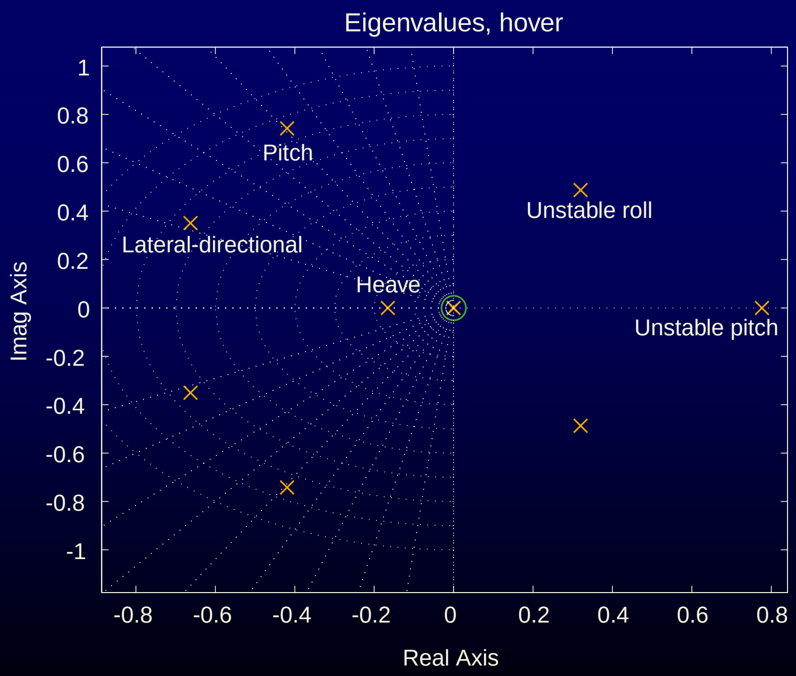




Aircraft Modeling

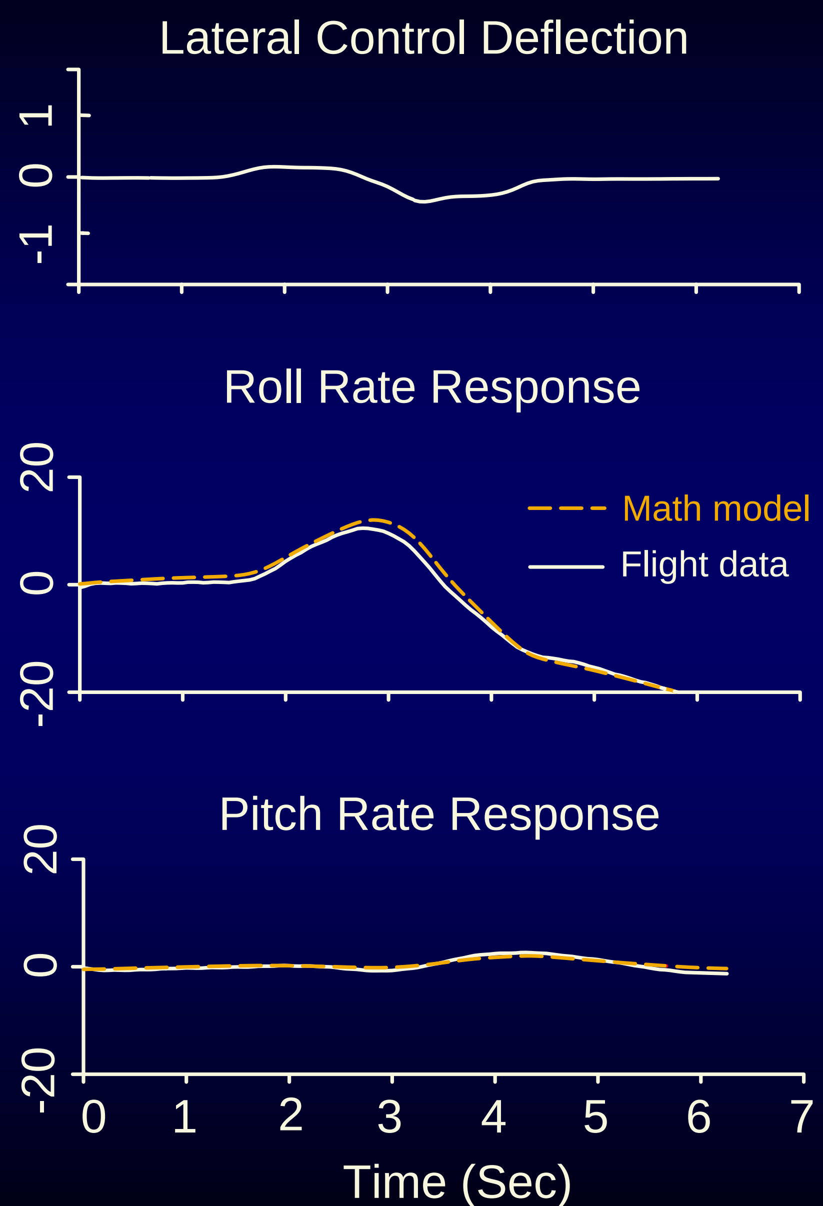
- Start with piloted frequency sweeps of unaugmented K-MAX
- 8-DOF (rigid-body + 2 rotor states) linear state-space model identified from flight data using CIFER®





Aircraft Modeling

- Verified in time domain using CIFER®



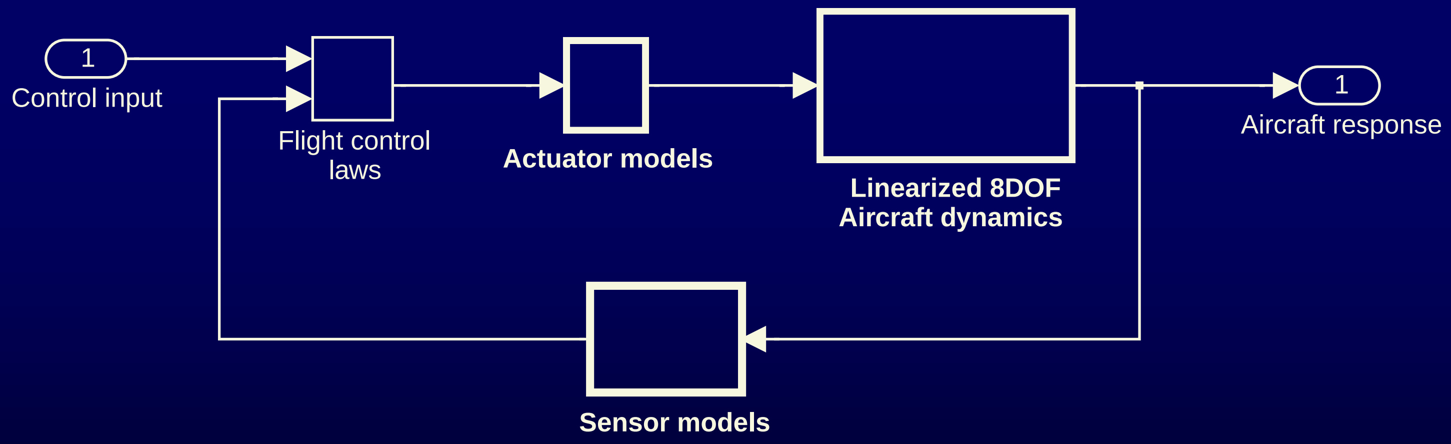
Ref: Jason Colbourne, et al., American Helicopter Society Forum, May 2000.

Aircraft Modeling

- Sensor dynamics
  - Equivalent delays estimated from manufacturer specs (25ms)
  - 2nd-order Padé approximations
- Actuator dynamics
  - Identified from bench-test frequency sweeps
  - 2nd-order systems (ω=20 r/s, ζ=.5)
  - Rate- and position-limiting

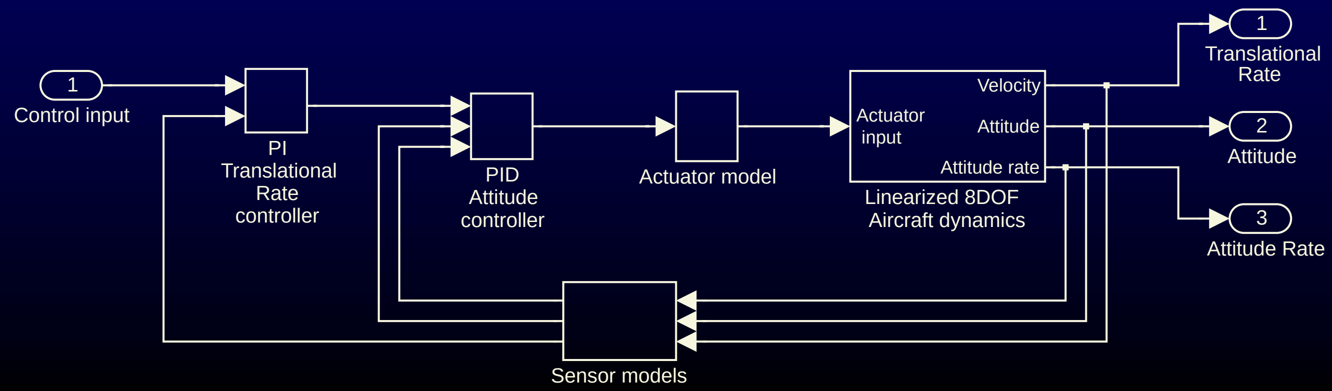
Aircraft Modeling

- Aircraft, actuator and sensor models implemented in Simulink block-diagram



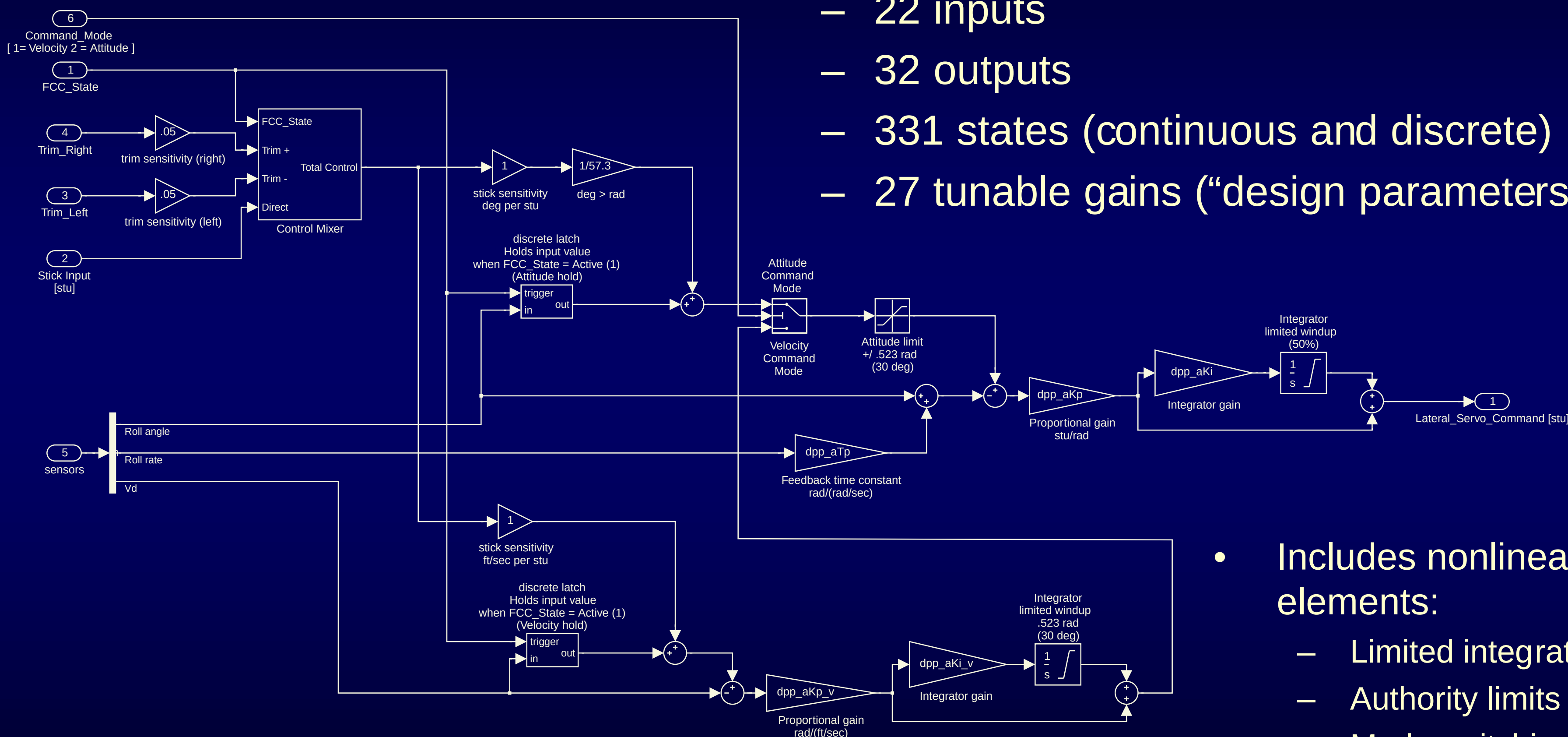
Control Law Development

- Inner Loops
  - Attitude Command / Attitude Hold
    - PID controller
  - Heading Command
    - PD controller
  - Altitude Rate Command
    - PD controller
- Outer Loops
  - Translational Rate Command
    - PI controller (or position feedback)
- Modeled in Simulink



Control Law Development

Lateral controller shown

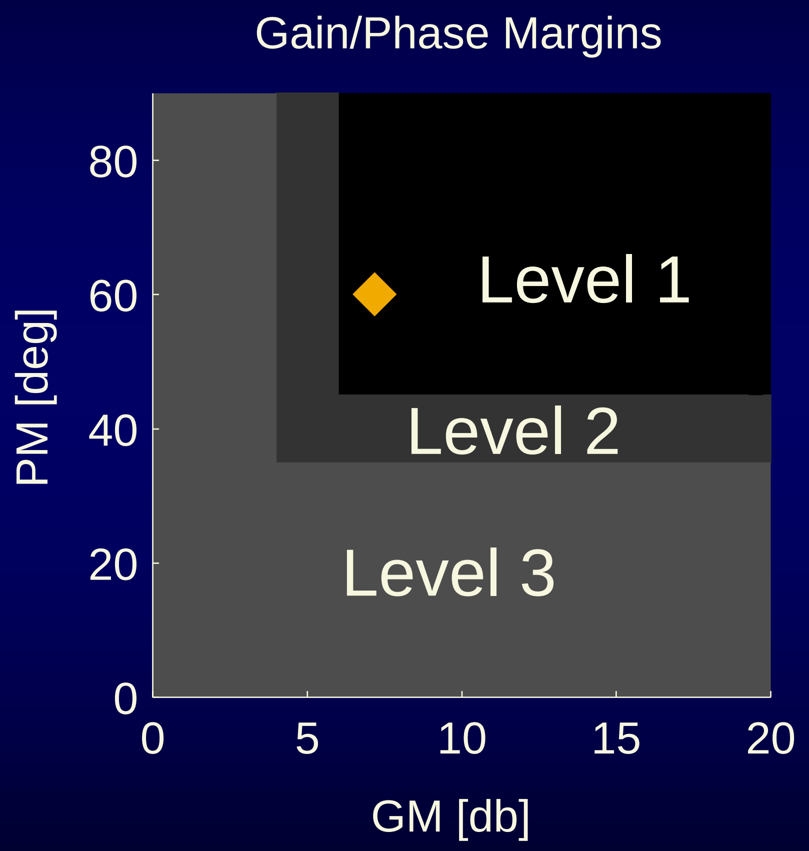


- Complete Simulink model:
  - 22 inputs
  - 32 outputs
  - 331 states (continuous and discrete)
  - 27 tunable gains (“design parameters”)

- Includes nonlinear elements:
  - Limited integrators
  - Authority limits
  - Mode switching

Control Law Development

- CONDUIT Optimization Engine:
  - Multi-objective optimization using FSQP
  - Adjusts design parameters (system gains) to meet requirements of specifications
  - Specifications represented graphically, 3 regions based on level of performance



- Categorizes specifications:
  - Hard
    - **must** be met
  - Soft
    - **should** be met, without violating Hard specs
  - Objectives
    - **minimized** after all specs satisfied

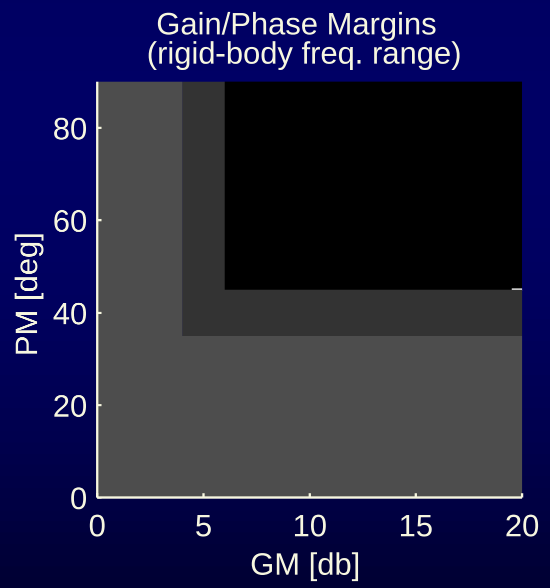
Control Law Development

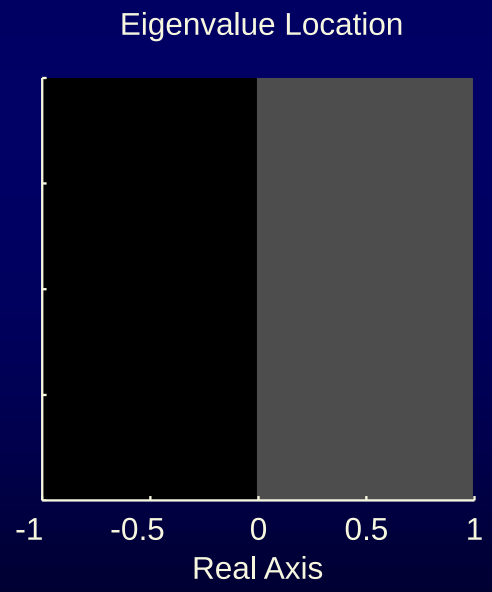
- Specification selection
  - Stability
  - Performance and “Handling Qualities”
  - Objectives

- Rationale
  - Airframe originally designed as a manned vehicle
  - Safety pilot on board demonstrator vehicle
  - Ground operator control will be VFR / simple tasks

Control Law Development

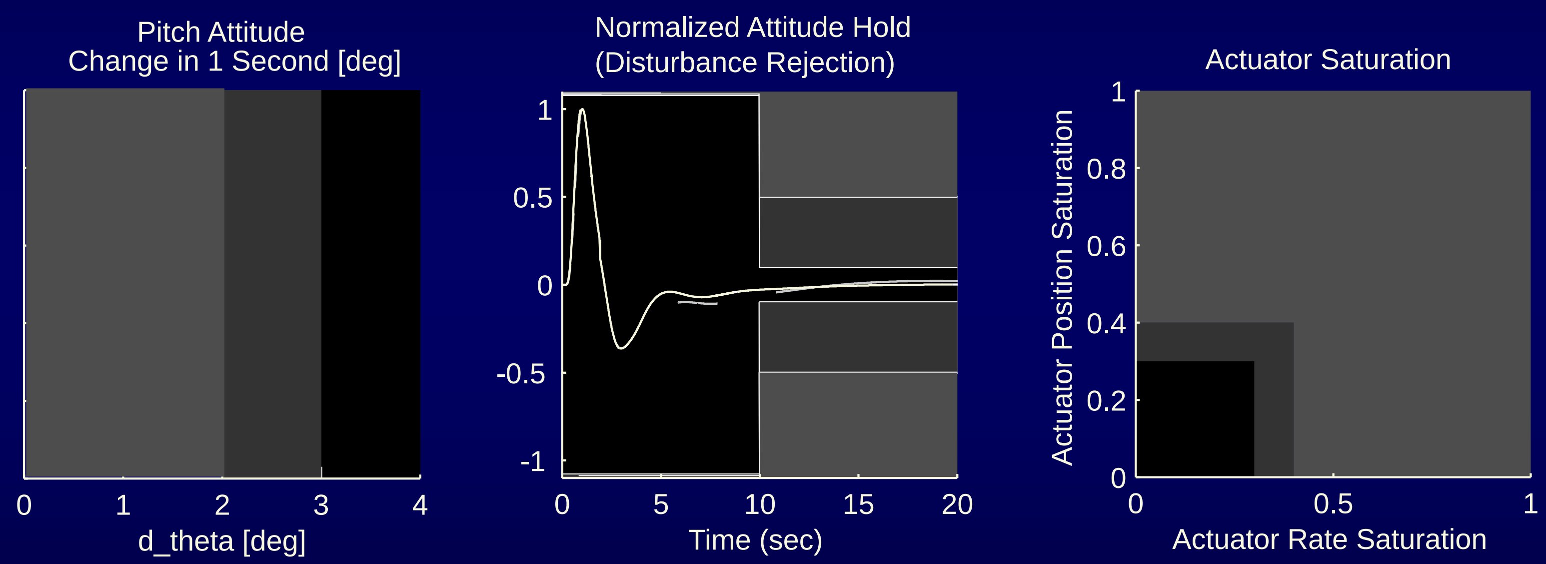
- Stability Specifications (Hard constraints)





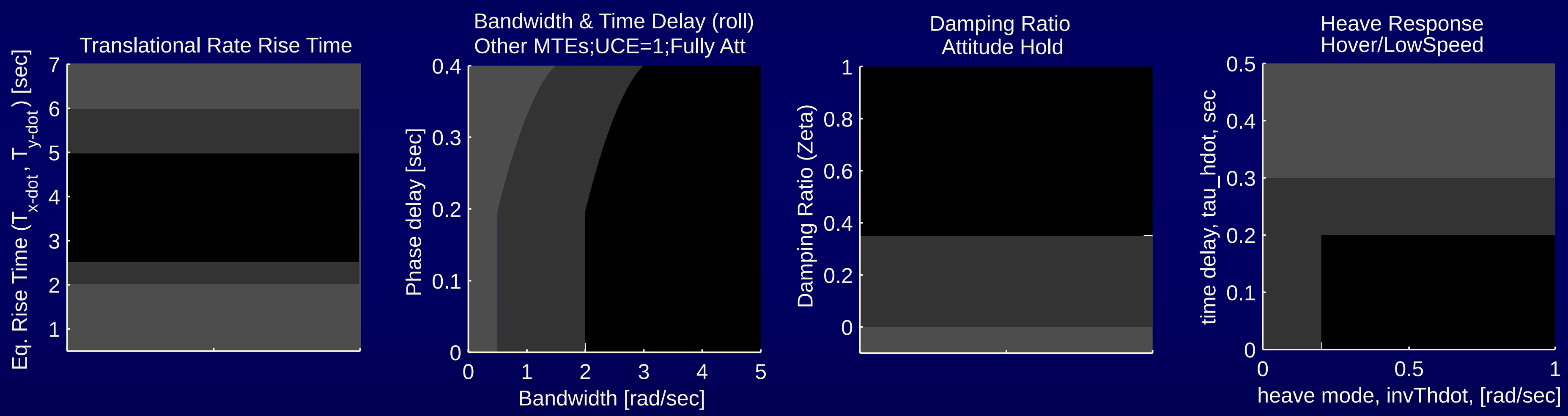
Control Law Development

- Performance Specifications (Soft constraints)



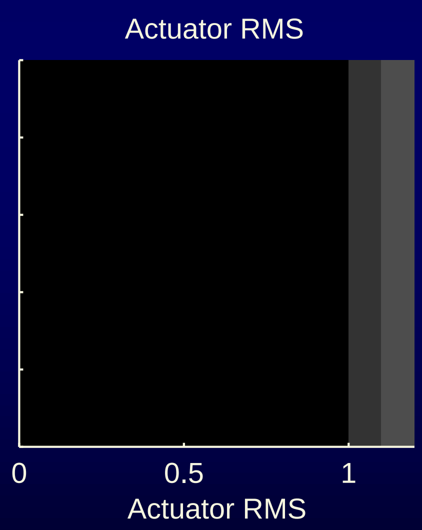
Control Law Development

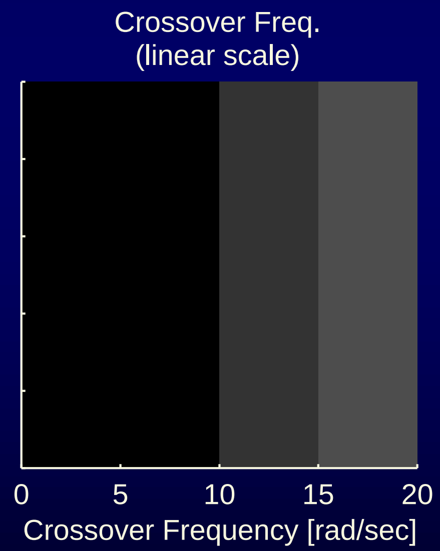
- Handling Qualities Specifications (Soft constraints)



Control Law Development

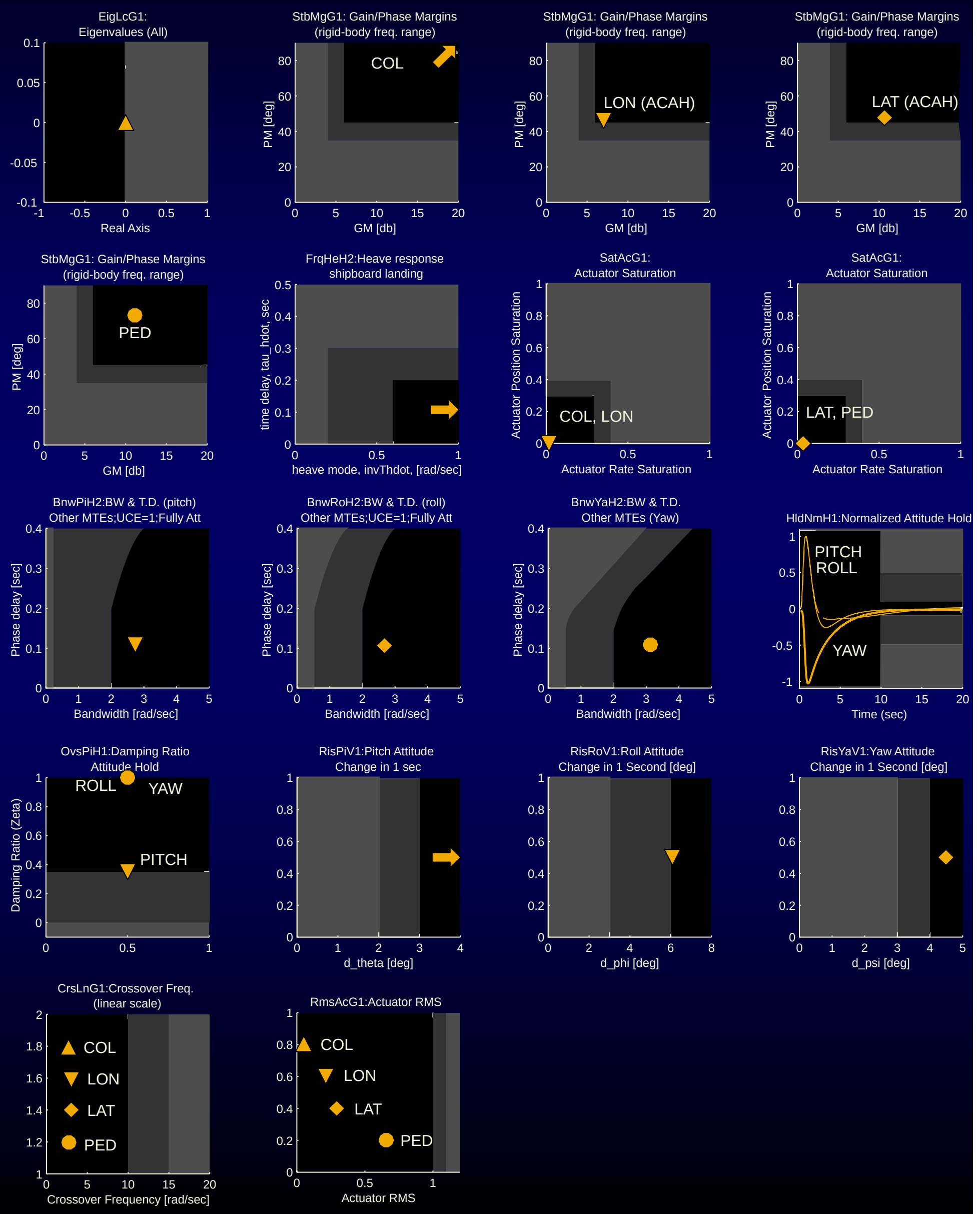
- Objective Specifications
  - Spec selection reduces actuator sizing, component fatigue, and noise sensitivity





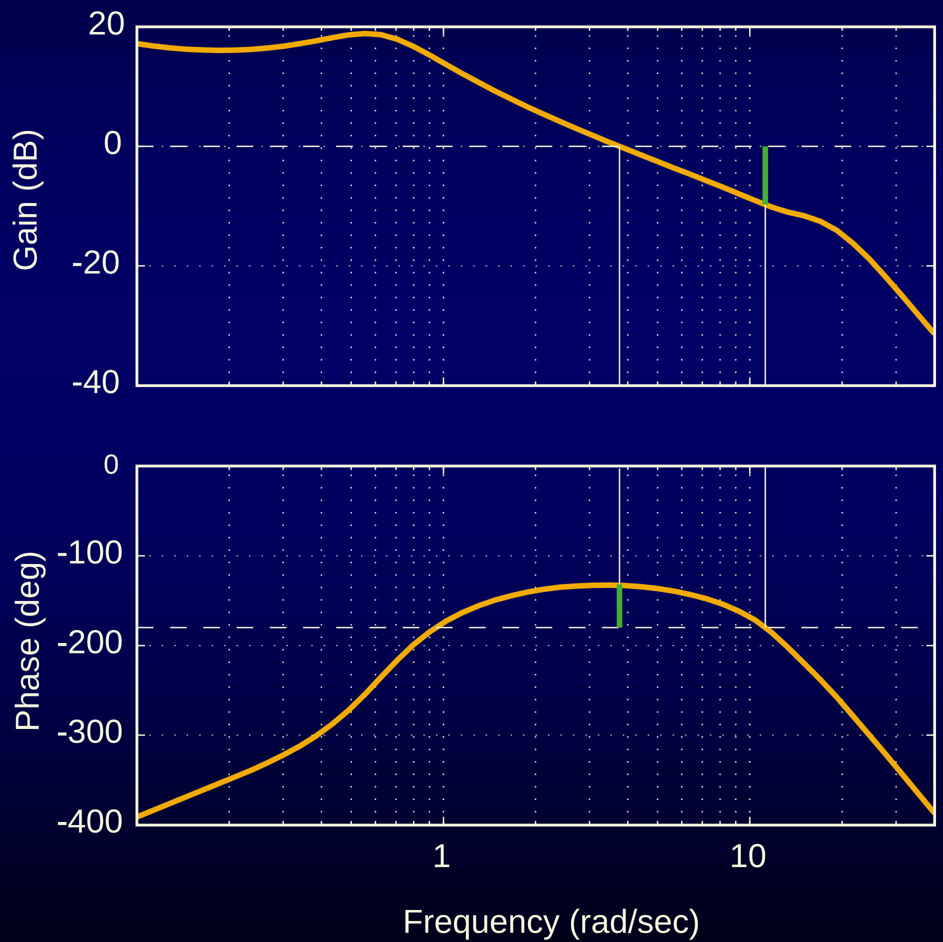
Control Law Development

- Control system gains tuned using CONDUIT
  - Initial tuning:
    - 27 parameters
    - 33 specifications
  - All specifications satisfied (Level 1)
  - RMS actuator position and crossover frequency minimized



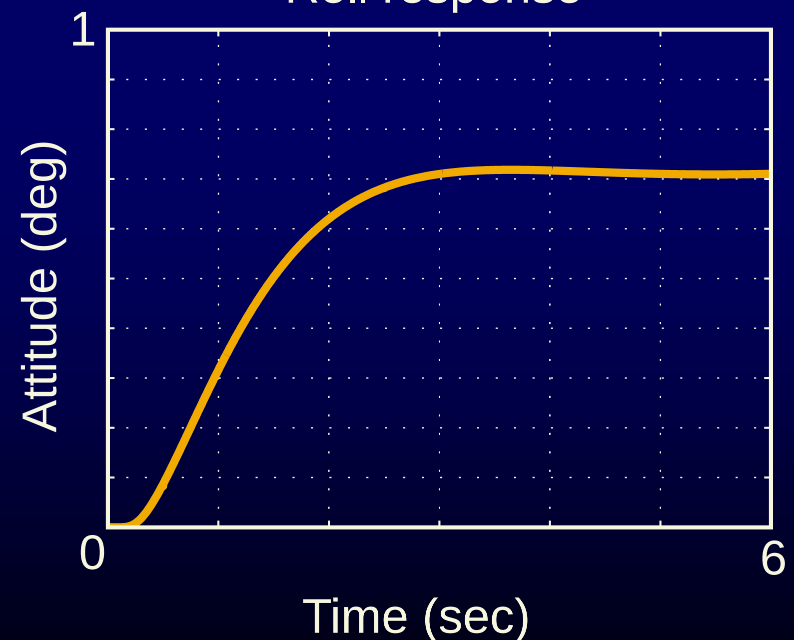
Control Law Development

Lateral Stability Margins (Initial):
PM = 46.8 deg. (ω_c = 3.75 rad/sec)
GM = 9.7 dB, (ω_{180} = 11.23 rad/sec)



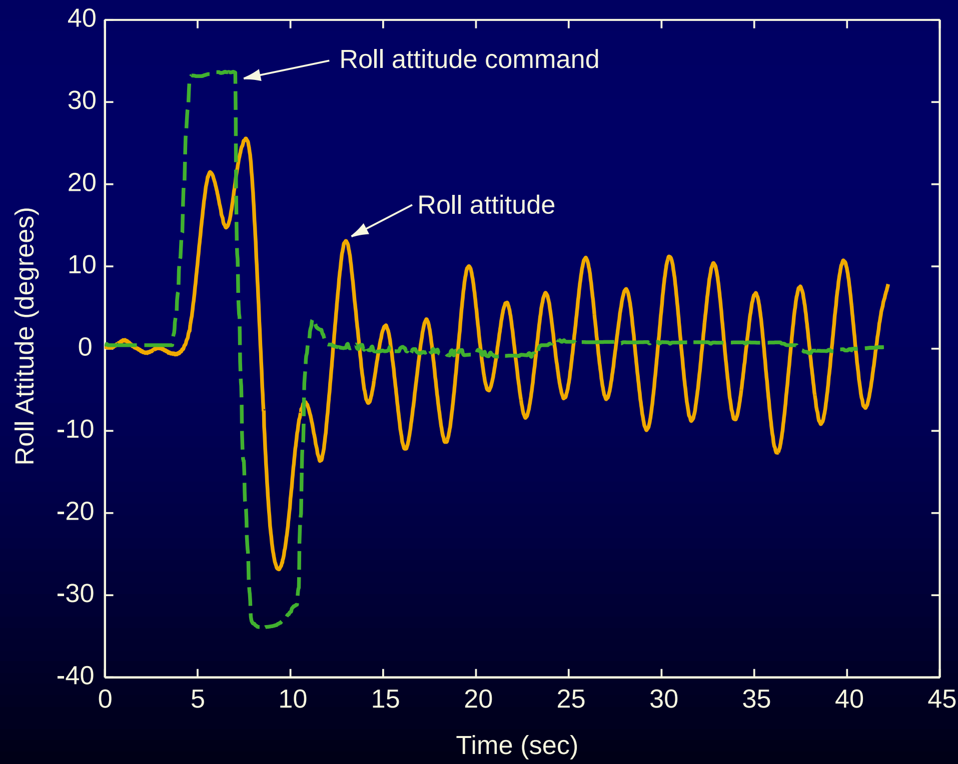
- Conditionally stable lat & lon
- Model predicts stable, well-damped responses

Roll response



Flight Test

- First flight test with CONDUIT-tuned gains
- Aircraft responses did not agree with model (lon and lat)



Flight Test

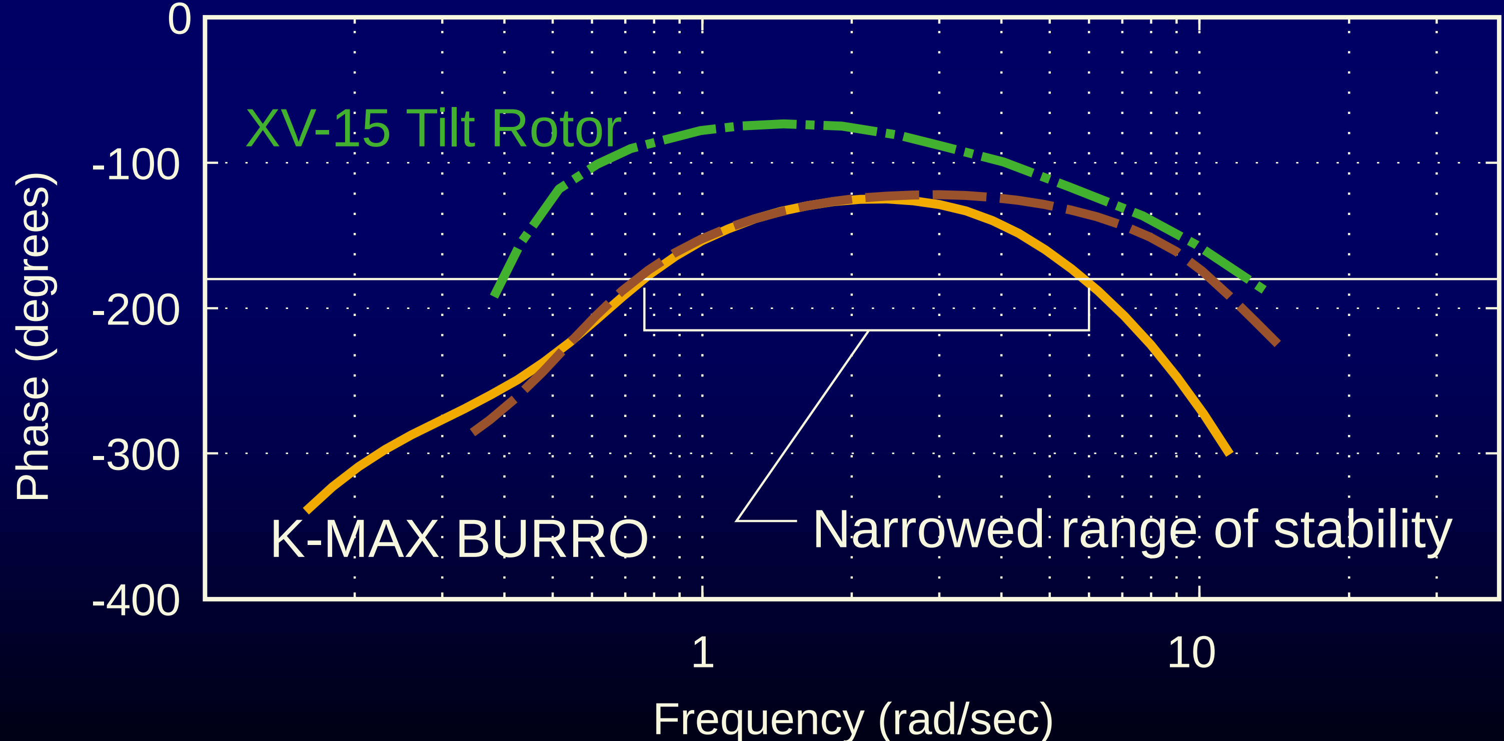
- Looking for source of discrepancy:
  - Lon and lat doublets flown closed-loop
  - CIFER® used to extract frequency responses
  - Actual sensor and actuator dynamics identified
- Equivalent time delay greater than originally estimated

Flight Test

Component	Estimated Delay (ms)	Actual Delay (ms)
Actuators	50	107
Sensors	25	53
Computer	20	60
Filters	0	70
TOTAL	**95**	**290**

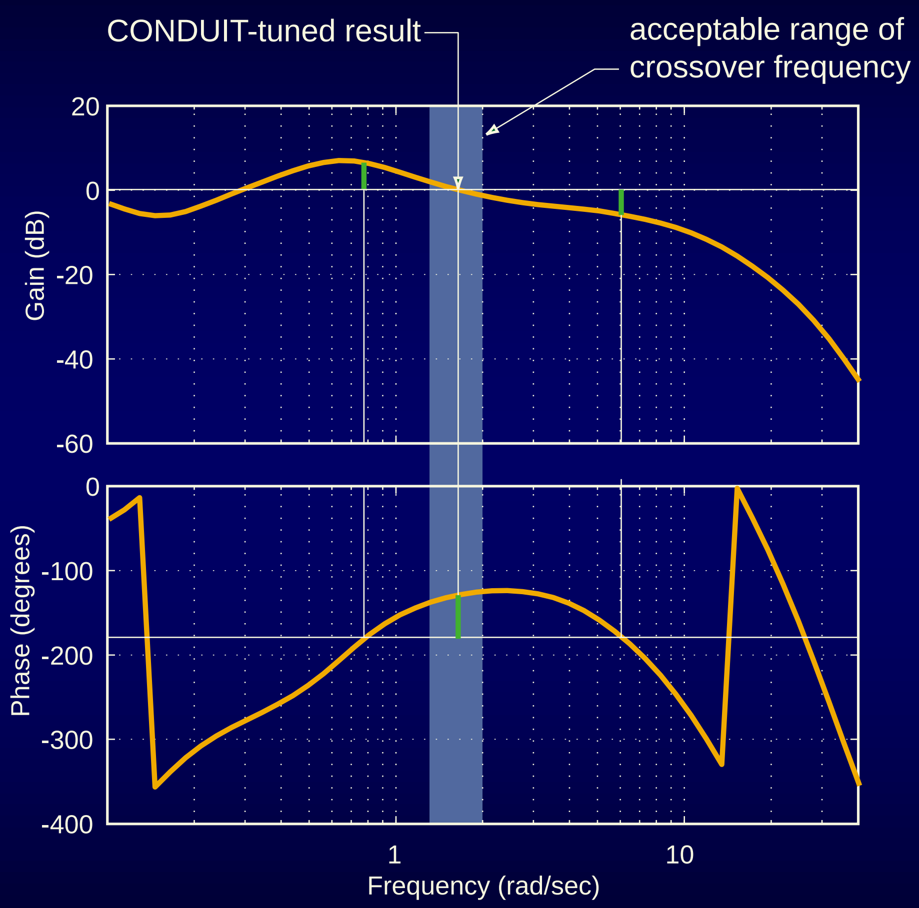
Flight Test

- Updated Simulink model with identified delays
- Added delay results in highly constrained system

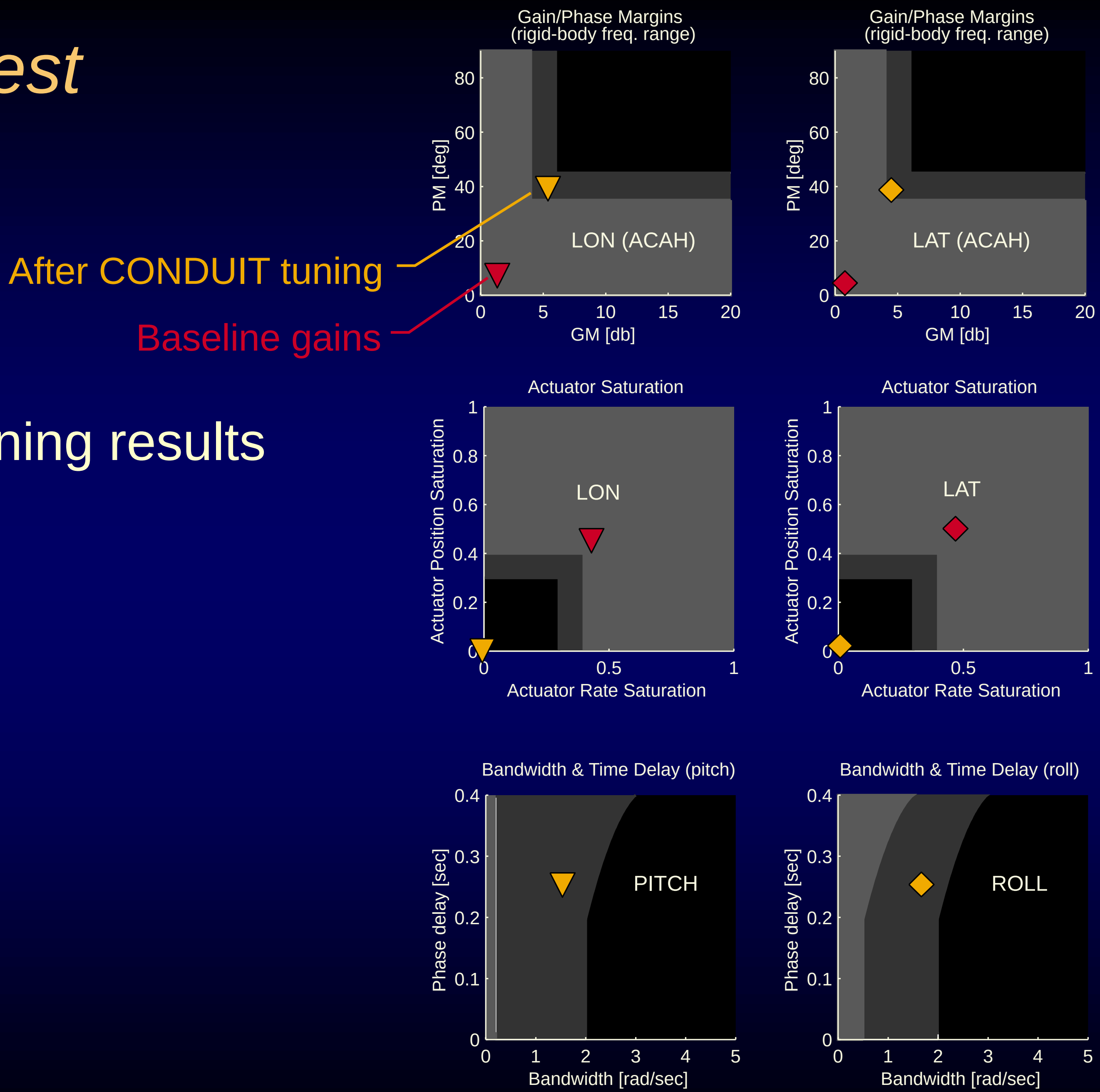


Flight Test

- Added lead filter to lon & lat attitude feedback
- FCS gains re-tuned with CONDUIT
- CONDUIT successfully traded off phase margin for gain margin



Flight Test

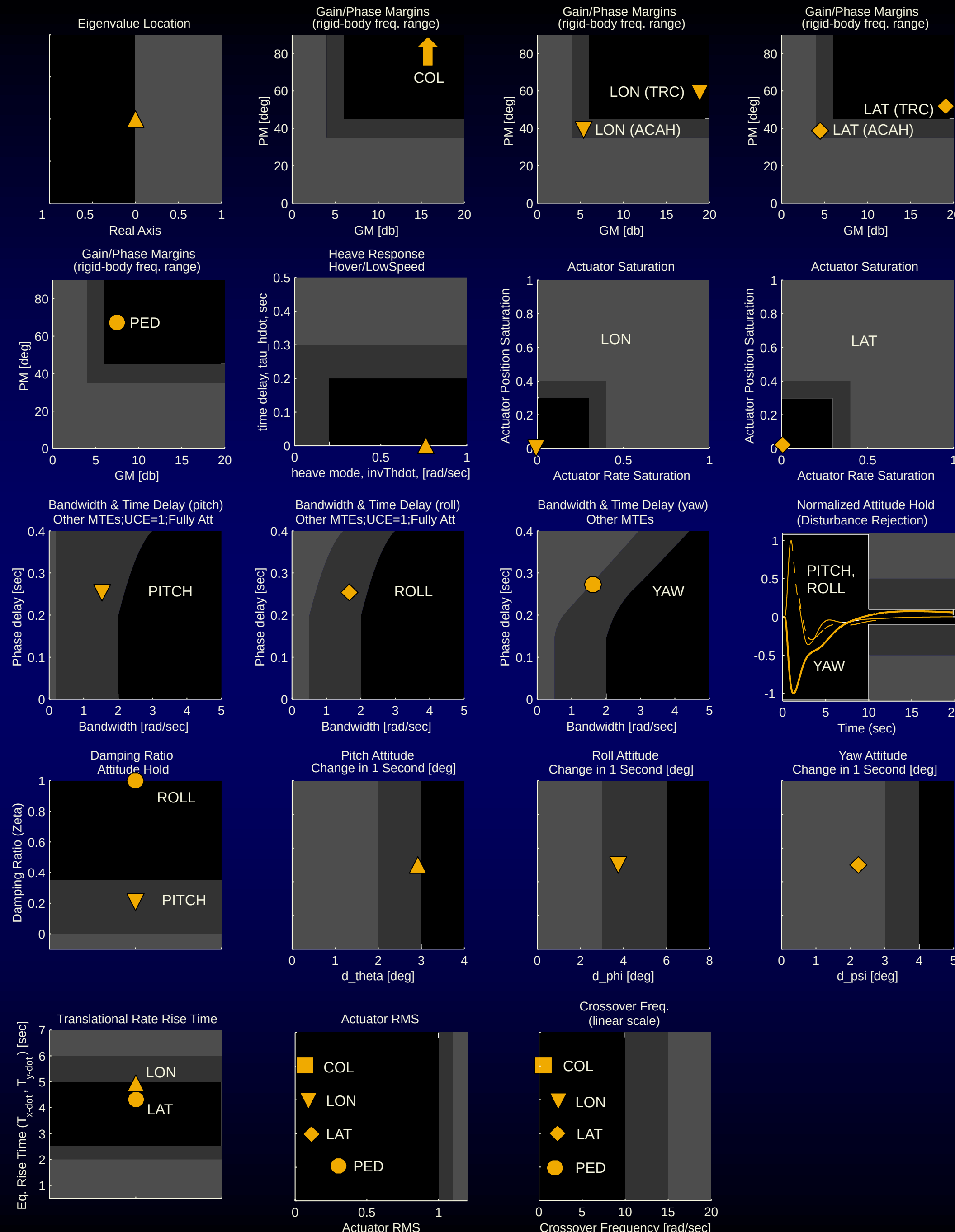


- CONDUIT tuning results

Flight Test

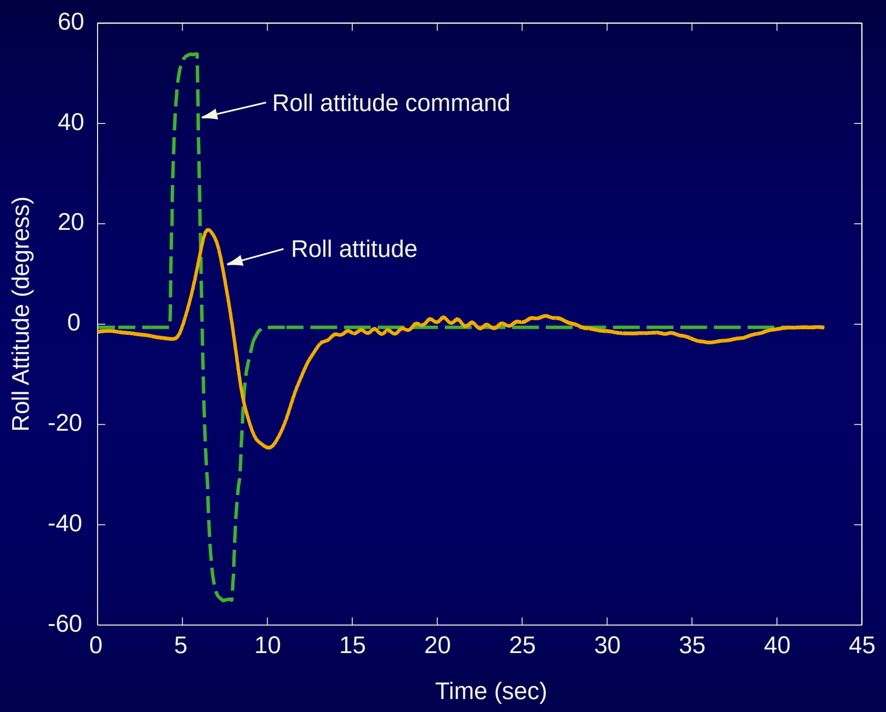
CONDUIT results:

- Level 2 (8 specs)
- Reduced bandwidth



Flight Test

- Roll response much improved; model responses agree well with flight results



Flight Test

- BURRO successfully demonstrated to USMC nine months after start of development

Conclusions

- Design space is very limited
  - Aircraft dynamics
  - Control system hardware
  - CONDUIT was able to extract the best achievable performance within design limitations
- High frequency dynamics were key driver of closed-loop performance
  - CIFER was useful in identifying system elements
- Advanced design tools allowed rapid development of a successful UAV
  - 9 month time span
  - Recovery from added delay

Current and Future Work

- Build 1 of K-MAX BURRO UAV successfully demonstrated to USMC
- Build 2 now in development
- 2000-lb loaded hover
  - 10-DOF EOM and CIFER ident complete
  - FCS design complete
- 5000-lb case in development
- Envelope expansion to 70 KTAS in progress

Questions?

For additional information:

http://caffeine.arc.nasa.gov

http://uavinfo.homepage.com