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

UAV Control Design
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

- Cockpit Display Development
- Math Model Development
- A/C Model
- Controller
- Auto Code
- Matlab SIMULINK
- Pilot Inceptors
- Out-the-window Displays
- RIPTIDE SHARED MEMORY
Design Methods

- Specifications
- Design
- Development
- Simulation
- Flight Test

Flight Vehicle Development Cycle
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
- Broad-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

Traditionally, UAV control design involves:
- **Design**: Manual, little or no optimization, stop when "good enough"
- **Simulation**: Not real time, not "pilot in the loop"
- **Analysis**: Manual, subjective, guesswork
- **Flight Test**: Slow, expensive, risky

In contrast, the state-of-the-art approach uses:
- **Design**: Multi-objective optimization
- **Simulation**: CONDUIT (NRT), RIPTIDE (RT, piloted)
- **Analysis**: CIFER, automated, accurate, objective
- **Flight Test**: Fewer hours required, higher initial confidence
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®

**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
    \((\omega=20 \text{ r/s, } \zeta=.5)\)
  - 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

- 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)

- Gain/Phase Margins (rigid-body freq. range)

- Eigenvalue Location

UAV Control Design
Control Law Development

- Performance Specifications (Soft constraints)

Pitch Attitude Change in 1 Second [deg]

Normalized Attitude Hold (Disturbance Rejection)

Actuator Saturation

Actuator Position Saturation

Actuator Rate Saturation
**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. ($\omega_c = 3.75$ rad/sec)
GM = 9.7 dB, ($\omega_{180} = 11.23$ 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

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<tr>
<th>Component</th>
<th>Estimated Delay (ms)</th>
<th>Actual Delay (ms)</th>
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<tr>
<td>Actuators</td>
<td>50</td>
<td>107</td>
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<tr>
<td>Sensors</td>
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<td>60</td>
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<td>Filters</td>
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<td>70</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>95</strong></td>
<td><strong>290</strong></td>
</tr>
</tbody>
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Flight Test

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

![Graph showing frequency response of K-MAX BURRO and XV-15 Tilt Rotor with narrowed range of stability.]

UAV Control Design
**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

After CONDUIT tuning
Baseline gains
### 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