Digital Autoland Control Laws using Direct Digital Design and Quantitative Feedback Theory

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AIAA Guidance, Navigation, and Control Conference
23 August 2006
Outline

- Introduction
- Problem Definition
- Research Objectives
- Aircraft Model
- Digital Controller Synthesis
- Simulation Examples
- Conclusions and Future Work
Introduction

- **Why Autoland?**
  - Landing is most difficult phase of flight
  - Most UAV damage is caused by human errors during takeoff and landing

- **Current Autoland Systems**
  - Small/Micro UAVs
  - Large UAVs

- **Proportional-Integral (PI) Controller**
  - Performance, robustness
  - Limited instrumentation
  - Simple and effective

- **Quantitative Feedback Theory (QFT) Controller**
  - Offers robust performance amidst structured model uncertainties
  - Limited instrumentation
  - Controller limitations are obvious early is design process
Problem Definition

- **Approach**
  - Localizer Tracker
  - Glideslope Tracker
  - Airspeed Command and Hold

- **Flare**
  - Airspeed Command and Hold
  - Automatic Flare

\[ h = h_{\text{flare}} e^{\frac{1}{\tau}} \]
\[ \tau = 1.99 \text{ sec} \]
\[ h_{\text{flare}} = 17.47 \text{ ft} \]
Research Objectives and Assumptions

- Develop an approach and automatic landing controller that:
  - Works with existing approach architecture (ILS CAT III)
  - Is easily adaptable to other vehicle platforms
  - Provides good performance to prevent damage to the aircraft
  - Is robust to model uncertainties and external disturbances such as wind and turbulence

- Assumptions
  - Precision guidance is available to the flare height
  - Aircraft is equipped with radar altimeter for precision height information
  - Moderate turbulence will be worst encountered
  - Noise not included on sensors
  - Faults and failures not encountered
Aircraft Model

- **Rockwell Commander 700**
  - Assume dynamics similar to a medium size UAV
  - Simulated in Texas A&M Engineering Flight Simulator
    - Fixed base simulator
    - Real-time, high fidelity, 6 DOF nonlinear simulator
- Control surface actuators modeled by first order transfer function with a 0.1 sec time constant
- Linear system identification used to generate non-parametric state-space models
# Aircraft Model

- **Model Uncertainties**
  - Due to modeling limitations
  - Added to select stability derivatives

### Lateral/Directional

<table>
<thead>
<tr>
<th>Derivative</th>
<th>Importance</th>
<th>Accuracy</th>
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</thead>
<tbody>
<tr>
<td>$C_{y\beta}$</td>
<td>7</td>
<td>±20 %</td>
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<tr>
<td>$C_{i\beta}$</td>
<td>10</td>
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<tr>
<td>$C_{n\beta}$</td>
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<td>$C_{yp}$</td>
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<td>50</td>
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<tr>
<td>$C_{lp}$</td>
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<td>15</td>
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<td>$C_{np}$</td>
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<td>90</td>
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<tr>
<td>$C_{yr}$</td>
<td>4</td>
<td>30</td>
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<tr>
<td>$C_{ir}$</td>
<td>7</td>
<td>40</td>
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<tr>
<td>$C_{nr}$</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>$C_{i\delta a}$</td>
<td>10</td>
<td>25</td>
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### Longitudinal

<table>
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<tr>
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<th>Importance</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>$C_{Le}$</td>
<td>10</td>
<td>±25 %</td>
</tr>
<tr>
<td>$C_{Da}$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$C_{ma}$</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>$C_{Lu}$</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>$C_{Du}$</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>$C_{mu}$</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>$C_{Lq}$</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>$C_{Dq}$</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>$C_{mq}$</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>$C_{L\delta c}$</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>$C_{D\delta r}$</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>
Digital Controller Synthesis

- Sample frequency of 10 Hz determined to give:
  - Good performance
  - Prevent aliasing
  - Prevent processor overload

- Proportional-Integral (PI) Controller
  - Gains chosen using z-plane root locus
  - Good performance
  - Robustness (6 dB gain margin, 45 deg phase margin)
  - Avoid excessive position and rates

- Quantitative Feedback Theory (QFT) Controller
  - Plant templates define region of uncertainty
  - Stability bounds and tracking bounds
  - Controller synthesis
  - Pre-filter synthesis
QFT Previous Work

- Bossert, 1994 describes a pitch attitude command and hold for a business jet and fighter
- Wu, et. al, 1998 documents the design of a lateral/directional controller
- Sheldon, et. al, 1994 describes the development and flight test of a small UAV inner-loop controller
- Horowitz, et. al, 1985 documents a full envelope flight control system for the F-16
- Most of the research in QFT has focused on inner-loop control
Digital Controller Synthesis

- QFT Controller Synthesis – Pitch Angle Command and Hold
  - Plant templates define region of uncertainty for each frequency
  - Six frequencies chosen: \( \omega = 0.1, 1, 2, 5, 15, 30 \) rad/sec
  - Stability bounds chosen for:
    - GM = 5.3 dB
    - PM = 49 deg
  - Tracking bounds chosen for:
    - 2 sec < \( t_r \) < 5 sec
    - PO < 20 %
Digital Controller Synthesis

- QFT Controller Synthesis – Pitch Angle Command and Hold
- Controller Design
  - Without Controller
  - With Controller
  \[ G(z) = \frac{0.853(z - 0.958)(z - 0.955)}{(z - 1)(z - 0.776)} \]
Digital Controller Synthesis

- QFT Controller Synthesis – Pitch Angle Command and Hold
- Pre-Filter Design

- Without Pre-filter

- With Pre-filter

\[ F(z) = \frac{0.189(z - 0.543)}{(z - 0.913)} \]
Simulation Examples

- **Localizer Tracker**
  - **Initial Conditions**
    - 45 deg intercept angle
    - 6 nm from runway threshold
    - \( U_1 = 151.0 \text{ ft/sec (90 kts)} \)

- **Requirements**
  - \( d_{cross} < 27 \text{ ft} \)
  - \( \dot{\delta}_a < 15 \text{ deg/sec} \)
  - \( \delta_a < 10 \text{ deg} \)

![Graphs showing simulation examples for Localizer Tracker and Requirements with PI and QFT controllers.](Image)
Simulation Examples

- **Glideslope Tracker**
  - **Initial Conditions**
    - 4 nm from runway threshold
    - Below vertical beam
    - $U_1 = 151.0$ ft/sec (90 kts)
  - **Requirements**
    - $|h_{error}| < 5$ ft
    - $\dot{\delta}_e < 15$ deg/sec
    - $\delta_e < 10$ deg
    - $\dot{T} < 10$ %/sec

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- **PI**
- **QFT**
Simulation Examples

- **Automatic Flare**
  - Initial Conditions
    \[ h_{\text{flare}} = 17.47 \text{ ft} \]
    \[ \dot{h} = -8.78 \text{ ft/sec} \approx -526.8 \text{ ft/min} \]
  - Requirements
    \[ V_{S_{TD}} > -6 \text{ ft/sec} \quad \delta_e < 10 \text{ deg} \]
    \[ d_{\text{flare}} < 1,000 \text{ ft} \quad \dot{\delta}_e < 15 \text{ deg/sec} \]

- **PI**
  - ALT (ft)
  - VS (ft/sec)
  - \( \delta_e \) (deg)
  - \( \dot{\delta}_e \) (deg/sec)

- **QFT**
  - ALT (ft)
  - VS (ft/sec)
  - \( \delta_e \) (deg)
  - \( \dot{\delta}_e \) (deg/sec)
Simulation Examples

- Turbulence Robustness
- Localizer

<table>
<thead>
<tr>
<th></th>
<th>PI</th>
<th>QFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Successful (%)</td>
<td>95.6</td>
<td>96.2</td>
</tr>
<tr>
<td>$d_{\text{cross}}$ Average (ft)</td>
<td>-4.35</td>
<td>-1.33</td>
</tr>
<tr>
<td>$d_{\text{cross}}$ Standard Deviation (ft)</td>
<td>10.83</td>
<td>11.05</td>
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</tbody>
</table>

- Glideslope

<table>
<thead>
<tr>
<th></th>
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<th>QFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Successful (%)</td>
<td>100</td>
<td>98.4</td>
</tr>
<tr>
<td>$ALT_{\text{error}}$ Average (ft)</td>
<td>0.5</td>
<td>0.88</td>
</tr>
<tr>
<td>$ALT_{\text{error}}$ Standard Deviation (ft)</td>
<td>0.73</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Simulation Examples

- Turbulence Robustness
- Autoflare

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<thead>
<tr>
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<tbody>
<tr>
<td>Soft Landings (%)</td>
<td>100</td>
<td>99.6</td>
</tr>
<tr>
<td>Hard Landings (%)</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>$VS_{TD}$ Average (ft/sec)</td>
<td>-0.27</td>
<td>-0.52</td>
</tr>
<tr>
<td>$VS_{TD}$ Standard Deviation (ft/sec)</td>
<td>0.12</td>
<td>0.91</td>
</tr>
<tr>
<td>$d_{flare}$ Average (ft)</td>
<td>728</td>
<td>669</td>
</tr>
<tr>
<td>$d_{flare}$ Standard Deviation (ft)</td>
<td>82</td>
<td>223</td>
</tr>
<tr>
<td>$\theta_{TD}$ Average (deg)</td>
<td>0.45</td>
<td>0.08</td>
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<tr>
<td>$\theta_{TD}$ Standard Deviation (deg)</td>
<td>0.36</td>
<td>0.93</td>
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PI:

QFT:
Simulation Examples

- Model Robustness
  - Localizer

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<tr>
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<tr>
<td>Percent Successful (%)</td>
<td>14</td>
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<tr>
<td>$d_{cross}$ Average (ft)</td>
<td>0.62</td>
</tr>
<tr>
<td>$d_{cross}$ Standard Deviation (ft)</td>
<td>120.6</td>
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Simulation Examples

- Model Robustness
- Glideslope

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<tr>
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<td>PI</td>
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<tr>
<td>Percent Successful (%)</td>
<td>41.7</td>
</tr>
<tr>
<td>$ALT_{error}$ Average (ft)</td>
<td>8.3</td>
</tr>
<tr>
<td>$ALT_{error}$ Standard Deviation (ft)</td>
<td>5.6</td>
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PI

QFT

**Simulation Examples**

- Model Robustness
- Glideslope

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**Simulation Examples**

- Model Robustness
- Glideslope
Simulation Examples

- Model Robustness
- Autoflare

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<td>16</td>
<td>96</td>
</tr>
<tr>
<td>Hard Landings (%)</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Damage Landings (%)</td>
<td>67</td>
<td>2</td>
</tr>
<tr>
<td>$VS_{TD}$ Average (ft/sec)</td>
<td>-15.3</td>
<td>-0.52</td>
</tr>
<tr>
<td>$VS_{TD}$ Standard Deviation (ft/sec)</td>
<td>9.3</td>
<td>0.99</td>
</tr>
<tr>
<td>$d_{flare}$ Average (ft)</td>
<td>109</td>
<td>669</td>
</tr>
<tr>
<td>$d_{flare}$ Standard Deviation (ft)</td>
<td>278</td>
<td>223</td>
</tr>
<tr>
<td>$\theta_{TD}$ Average (deg)</td>
<td>-5.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$\theta_{TD}$ Standard Deviation (deg)</td>
<td>9.4</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Conclusions and Future Work

- Both controllers provide good performance
- In turbulence, both controllers show good robustness
- Both controllers show robustness to model uncertainties in still air
- In turbulent air, the QFT controller shows significantly better robustness to model uncertainties
  - PI controller meets specifications 16% of the time
  - QFT controller meets specifications 96% of the time

Future Work
- Examine crosswinds
- Evaluate various approach types
- Combination of PI and QFT techniques for inner and outer-loops
Questions?