Back-up Slides
Motivation

• World GDP will average 3.2% growth per year
• World air cargo traffic will grow at 6.4% per year

Airbus Global Market Forecast, Sept 2002
Motivation

- Alaska Airlines saw average fuel price increase from 90 cents per gallon in 2003 to $1.10 per gallon in January to $1.30 per gallon in March of this year – a 44% increase over last year.

- Airlines in the US have spent over $1 billion more on fuel during the first quarter of 2004 as compared to the same period in 2003.

- American Airlines: Will spend $400 million more on fuel this year compared to last year.

- United Airlines: Every penny increase in the price of a gallon of fuel costs $22 million per year.

- Fuel is 2nd-largest airline expense next to personnel.

- Fuel is 12-18% of total airline costs.
New Aircraft Feasibility Study

- Innovative ideas for new aircraft
  - If formation flight becomes common, may be included
  - May open new missions to formation flight

- New ideas can increase range and fuel benefits

- Affordable used aircraft available for cargo carriers

- If a new aircraft development program already exists, the formation flight system can be integrated, would be same as modification programs.

- Even with optimistic assumptions, range and fuel benefits of an aircraft designed for formation flight, over a modified aircraft, do not offset new aircraft development costs
Mission Overview

Minimum fuel savings upper and lower bound in function of the precision of the station-keeping
System Goals

- The benefits of formation flight to the existing commercial cargo system are the easiest to quantify, VALUE = $$$
- The development and implementation would be similar across all applications
- Preliminary results are easier to obtain and can be applied to military or new aircraft programs
- Commercial missions are simple and scheduled
- Military:
  - Value is difficult to quantify
  - Missions are more variable and aircraft are less utilized than commercial aircraft
- Justification for development is easier to make in commercial terms
- Large share of the commercial cargo market is at stake
Architecture Decisions

Control Methodology

Communications Equipment

Topology

Data Flow

Leader Follower

RF
Lasers

All
Wingmen

All
Wingmen

Leader Follower with Performance Seeking

RF
Lasers

All
Wingmen

All
Wingmen

One Way

RF
Lasers

All
Wingmen

All
Wingmen
Architectures - Formation Shapes

Staggered chevron

Rotating echelon

Both optimum in terms of fuel savings
If we want range increase: need for rotation
Evaluation – Performance Benefits

Minimum induced drag benefit in function of the precision for the follower in a two-aircraft formation

- **Fuel Savings**
  - 5%
  - 7.5%
  - 8.3%
  - 8.7%

- **Upper bound**
  - 8.1%
  - 12.2%
  - 13.5%
  - 14.2%

- **Lower bound**

**Graph Details**
- **Y-axis**: Benefit in induced drag (%)
- **X-axis**: Precision (span)

**Legend**
- **vortex lattice**
- **horseshoe vortex core = 0.03 span**
- **F/A-18 measurements**
  - M=0.56; z=25,000 feet
  - longitudinal separation = 3 spans
- **F/A-18 measurements**
  - M=0.86; z=36,000 feet
  - longitudinal separation = 3 spans
Evaluation – Performance Benefits

Minimum fuel savings upper and lower bound in function of the precision of the station-keeping

![Graph showing fuel savings in relation to precision for different aircraft numbers](image)
Control Architectures - Options

- Model-based Methods
  - More traditional, proven in other applications
  - Smaller development effort & risks to implement

- Types
  - Trajectory Tracking
    - Simplest to implement and predict behavior
    - Operationally inflexible
  - Leader-Follower
    - Proven outside of vortex in flight tests
    - Theoretically modeled optimal position not necessarily so in practice
    - Many different ways of implementing
      - Leader, front and hybrid modes
      - Centralized or decentralized
Control Architectures - Options

• Non Model-based Methods
  – Generally experimental, some use in loosely related applications
  – Larger development effort & risks to implement
  – Potentially greater performance benefits than model-based methods

  – Types
    • Performance Seeking
      – If working correctly will actually find the minimum drag location based on actual flight data
      – Easily side-tracked by local minima
      – Works better in conjunction with position-hold algorithm

    • Neural Networks
      – Relative position sensing not required
      – Requires comprehensive training set
      – Tough to certify due to unpredictability when a condition outside of the training set is encountered

    • Vortex Shaping
      – Requires extensive wing modifications (plus related development cost) to existing aircraft
      – Theory not yet well developed enough to predict effects of changing wing geometry on vortex position
Control Architectures - Most Promising

• Leader-Follower Methods
  – Some obvious problems with all other methods, including:
    • Certification issues
    • Large uncertainty/risks associated with unproven technologies
    • Simply cannot meet performance requirement

• Three better implementations of this method
  – Centralized Leader-Follower
  – Centralized Leader-Follower with Performance Seeking
  – De-Centralized Leader-Follower
Centralized vs. Decentralized

- **Centralized**
  - Higher level system decision-making
    - Enhanced coordination
    - Greater performance level
  - Lower algorithm complexity
  - Preferred for simple missions where performance is a priority
    - Commercial flight

- **Decentralized**
  - Distributed decision-making can result in conflicting decisions
  - Robust, flexible
  - Formation reconfiguration is easier
  - Lower information requirements
  - Preferred for complex missions, particularly where # of airplanes in formation is expected to change
    - UAVS
    - Other manned military operations such as bombing multiple targets
Control Architectures - Decision

• Centralized Leader-Follower:
  – Single leader aircraft within the formation that issues commands to all other aircraft
  – Leader:
    • Receives relative & absolute state information from all planes
    • Acts as DGPS base station
    • Issues commands designed to:
      – Maintain overall formation shape with planes offset by required amount
      – Anticipate planned future maneuvers (feed-forward)
  – Followers:
    • Receives state commands from leader, computes how to execute them
    • Sends aircraft state information to leader
Expected Control Performance

- Autonomous formation flight in the wingtip vortex has never been done!
- Expectation:
  - Control within 0.1b of required relative position may be achieved with this method
  - If not, performance-seeking control may be pursued as a further refinement
- Baselines:
  - NASA AFF project
    - Flight test with two F/A-18s, decentralized leader-follower
    - Out of vortex lateral/vertical accuracy +/- 9ft (~0.2b)
    - Algorithm NOT tweaked or optimized
  - Proud, Pachter, D’Azzo
    - Simulation with two F-16s, decentralized leader-follower
    - Met 0.1b performance requirement for level flight and maneuvering flight under the following changes:
      - Lead heading change of +/- 20 degrees
      - Lead velocity change of +/- 50ft/s
      - Lead altitude change of +/- 400ft
  - Centralized leader-follower would have similar results for these 2 aircraft configurations
  - Many other simulations using leader-follower strategies within this range
  - Subject matter experts (Deyst, How) optimistic method can achieve 0.1b accuracy based on experience with UAVs
## Position and Velocity Sensing - Options

### Possible solutions with required accuracy

<table>
<thead>
<tr>
<th>Solution</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Coupled Carrier-Phase Differential GPS and IMU | • Most conventional solution  
• Proven to work in NASA AFF flight tests and other formation applications | • Complexity in achieving desired accuracies  
• Occasional large errors when formation aircraft observe different satellite sets |
| Lasers                                        | • Low observability  
• Best accuracy, used as 'truth case' baseline for comparison to other methods  
• Small size  
• Already in use on all C5's, many potential space applications | • Highest cost  
• Level of accuracy really is not required  
• Unless omni-directional, must be directed  
• Reliability difficulties in some weather conditions |
| Optical Camera                                | • Once aimed, does not require continuous communications link | • Camera must be initially aimed using rougher position data  
• Requires target to have specially placed markings |
| Electromagnetic Pulses                        | • Low complexity  
• Sub-foot accuracies easily achieved  
• Possibly low cost, but a question mark | • Most unconventional, unproven solution  
• More development required, though can leverage existing radar technologies |

### Can have multiple systems for backup
- Collision avoidance, loss of primary sensors
Position and Velocity Sensing - Decision

- **Primary system:** Carrier-phase differential GPS and IMU
  - 0.2 in accuracy theoretically possible for surveying applications
  - 1 foot accuracy in relative position in practice for formation flight (NASA Dryden experiment)
  - Leader acts as DGPS base station for relative positioning and sends satellite errors through intra-formation communications system

- **Backup system:** Optical Camera
  - Different technology than primary system for robustness
  - Machine vision tracks markings placed on adjacent aircraft and uses size to determine separation
Communications - Options

- Possible solutions able to meet requirements

<table>
<thead>
<tr>
<th>Transmission Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Line of Sight</td>
<td>• Used for other many other common applications</td>
<td>• Additional antennas need to be installed on exterior of A/C</td>
</tr>
<tr>
<td></td>
<td>• Transmitters and receivers commercially available</td>
<td>• May have conflicts with other equipment or frequencies</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td>• Line of sight required for transmission</td>
</tr>
<tr>
<td>RF Satellite</td>
<td>• Currently in use for other commercial applications</td>
<td>• Higher cost</td>
</tr>
<tr>
<td></td>
<td>• Avoids line of sight requirement</td>
<td>• Half-second delay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Requires use of external satellite system</td>
</tr>
<tr>
<td>Laser, Infrared, Other</td>
<td>• Low observability</td>
<td>• Higher cost to implement</td>
</tr>
<tr>
<td></td>
<td>• Less likely to conflict with existing equipment</td>
<td>• Shorter range for infrared</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• May have weather issues</td>
</tr>
</tbody>
</table>
Communications: Why relay?

- Non-adjacent aircraft cannot be connected via direct RF links because aircraft in between block the Fresnel clearance zone necessary for radio transmission.
- HF band, which bounces off ionosphere, already too saturated, and has low data rate.
- Table shows size of 60% Fresnel zone necessary for RF comm for aircraft in configuration to the right with adjacent aircraft 7 spans apart.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Freq. (2.4 GHz)</th>
<th>Freq. (5.8 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B757</td>
<td>10.4 ft</td>
<td>6.7 ft</td>
</tr>
<tr>
<td>(125 ft span)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A380</td>
<td>15.0 ft</td>
<td>9.7 ft</td>
</tr>
<tr>
<td>(262 ft span)</td>
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</tr>
</tbody>
</table>

(Lateral offset is assumed to be small compared to longitudinal distance for purposes of estimate)

Calculated using Fresnel Zone calculator at:
http://www.firstmilewireless.com/cgi-bin/fresnel-calc.pl
Data Update Rate Available

- Calculation of available data rate:
  - Let each “message” contain data about one aircraft
  - Assume 20 32-bit numbers need to be transmitted per message to cover all data transfer
    - Includes approximately 9 aircraft states, DGPS errors for up to 5 satellites, aircraft ID, time of measurement, 4 control commands
  - Assume data rate at long distances at high altitude degraded from 11 Mbps on ground for commercial wireless technology to 3 Mbps = 3,000,000 bits per second (not $2^{20}$ bits)
  - For n aircraft in formation, if only one can transmit at a time, $n(n-1)$ messages must be sent to update all aircraft with all other aircraft information
  - Total of $20 \times 32 \times n(n-1)$ bits to update all aircraft
  - $n(n-1)/5000$ seconds for full system update

<table>
<thead>
<tr>
<th># of aircraft in formation</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full system update time</td>
<td>0.4 ms</td>
<td>1.2 ms</td>
<td>2.4 ms</td>
<td>4.0 ms</td>
<td>6.0 ms</td>
<td>8.4 ms</td>
<td>11.2 ms</td>
<td>14.4 ms</td>
<td>18.0 ms</td>
</tr>
</tbody>
</table>
Required Data Update Rate

- Function of how dynamic environment is
  - How quickly the vortex is moving around

- Want to update faster than the frequency of actual movement

- Basic range: 1-100Hz

- NASA AFF program had 40Hz local and 10Hz relative position and state rates
  - Starting point for the proposed system
Pilot Interface

- **Flight Display on ND 1 & 2:**
  - Same functions as the standard ND with a close-up view on the formation
  - Predictive display of the position of the surrounding planes with safety distance thresholds associated to alarms
  - Flying mode (leader/follower)
  - Graphical display of the route followed by the formation
Pilot Interface

• CDU pages dedicated to formation flight
  – Status and route of the formation:
    • Input set by the leader in “leader mode”
    • Updated automatically from the leader for planes in “follower mode”
  – Status of the formation software characteristics and the associated alarms (shown on the System Display)
    • Possibility to check how the system is running
    • Display of visual and acoustic alarms

Those pages can be similar to the ones already in use. It all depends on the autopilot system chosen for our concept.
Take-off configurations
Join-up configurations

$T_0$: First aircraft takes-off

$T_1 > T_0$

$T_2 > T_1$

$T_3 > T_2$

$\Delta t = 1$ to 2 min

$\Delta t = 1$ min

New AC joining
Break-away Procedures

1. Separation
2. Longitudinal
3. Lateral
4. Altitude
Landing configurations
Unexpected break-away Procedures

1. Catch-up
2. Problem is fixed: join-up the formation
3. Problem is not fixed: leaves the formation

Limit of responsibility for ATC

Climb
Slow down
Join-up
Minimum Separation Criteria

<table>
<thead>
<tr>
<th>n</th>
<th>2</th>
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<th>5</th>
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<tr>
<td>r</td>
<td>.50</td>
<td>.58</td>
<td>.70</td>
<td>.85</td>
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<tr>
<td>R</td>
<td>3.50</td>
<td>3.58</td>
<td>3.70</td>
<td>3.85</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Safety Responsibilities

- **Airport Ground Operations**
- **Take-off**
- **Formation Join-up**
- **Formation Flight**
- **Formation Break-away**
- **Landing**

**Unexpected Break-away**
- Remains inside the formation
- Leaves the formation
NAS Capacity & ATC Workload

Local Airspace capacity

1 cell

No Formation: Single AC only

3 formations of $n_1$, $n_2$, $n_3$ AC

Unexpected formation break-away

Temporary holding pattern

Temporary -but bearable- increase in workload

MAP: ZSE, ZLC, ZDV, ZKC, ZMP, ZAU, ZDB, ZNY, ZRW, ZOA, ZLA, ZAB, ZFW, ZDV, ZLC, ZMP, ZAU, ZDB, ZNY, ZRW, ZOA, ZLA, ZAB, ZFW

MAP: MEM, ZLC, ZDV, ZKC, ZMP, ZAU, ZDB, ZNY, ZRW, ZOA, ZLA, ZAB, ZFW, ZLC, ZDV, ZKC, ZMP, ZAU, ZDB, ZNY, ZRW, ZOA, ZLA, ZAB, ZFW

16.886: Final Presentation
May 5th, 2004
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<td><strong>R&amp;D</strong></td>
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<td>Simulation development</td>
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<td>Performance seeking</td>
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<td>Optical sensor development</td>
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<td>Alternate sensor research</td>
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<td>Simultaneous TO and landing</td>
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<td>Test planning</td>
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<td>Piloted FQ, vortex mapping.</td>
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<td>System testing outside vortex</td>
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<tr>
<td>Simulator testing</td>
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<tr>
<td>Extensive vortex mapping</td>
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<tr>
<td>System test inside of vortex</td>
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<td>Operational evaluation</td>
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<td>3+ A/C testing and cert</td>
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<td>Alternate A/C types</td>
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<td><strong>Manufacturing</strong></td>
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<td>Test a/c installation</td>
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<tr>
<td>Production kit manufacturing</td>
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<tr>
<td>Production installation</td>
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<tr>
<td>Alt A/C type mod and design</td>
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</tr>
</tbody>
</table>

Milestone: System certified for two aircraft in formation
Milestone: Operational aircraft flying formation
<table>
<thead>
<tr>
<th>Event</th>
<th>Consequence</th>
<th>Severity</th>
<th>Probability</th>
<th>Mitigation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader's communication system fails</td>
<td>No aircraft know where to go</td>
<td>Low</td>
<td>Moderate</td>
<td>Another aircraft is prepared to become leader when it stops hearing from leader</td>
</tr>
<tr>
<td>Two aircraft think they're leaders</td>
<td>Possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>Make sure this can't happen</td>
</tr>
<tr>
<td>Non-leader transmit failure</td>
<td>Leader doesn't know where all aircraft are, possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>When communication stops, break up</td>
</tr>
<tr>
<td>Non-leader receive failure</td>
<td>Aircraft doesn't know where to go (it leaves the formation)</td>
<td>Low</td>
<td>Moderate</td>
<td>When communication stops, break up</td>
</tr>
<tr>
<td>Position sensor failure</td>
<td>Leader gets wrong data, possible collision</td>
<td>High</td>
<td>Low</td>
<td>Make sure prob is low with redundancy in position sensors</td>
</tr>
<tr>
<td>Leader has an engine failure</td>
<td>Leader loses thrust, slows down, possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>Enough spacing, all aircraft can act as leaders, breakup planning</td>
</tr>
<tr>
<td>Non-leader has an engine failure</td>
<td>Same as above (unless if it's the last aircraft)</td>
<td>High</td>
<td>Moderate</td>
<td>Enough spacing to handle this event, communication of warnings to other aircraft</td>
</tr>
<tr>
<td>Common mode engine failure (e.g. formation flies through ash)</td>
<td>Possible collision</td>
<td>High</td>
<td>Low</td>
<td>Make breakup plan robust to common problems</td>
</tr>
</tbody>
</table>
## Hazard Analysis 2

<table>
<thead>
<tr>
<th>Event</th>
<th>Consequence</th>
<th>Severity</th>
<th>Probability</th>
<th>Mitigation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common mode communication failure (e.g. static electricity)</td>
<td>Possible collision</td>
<td>High</td>
<td>Low</td>
<td>Breakup must not require communication</td>
</tr>
<tr>
<td>Pilot misinterprets display and takes over when he shouldn't</td>
<td>Possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>Make display &amp; warnings clear as possible</td>
</tr>
<tr>
<td>Pilot misinterprets display and doesn't take over</td>
<td>Possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>Make display &amp; warnings clear as possible</td>
</tr>
<tr>
<td>Software error in leader's position software</td>
<td>Possible collision</td>
<td>High</td>
<td>Low</td>
<td>Good software planning &amp; testing</td>
</tr>
<tr>
<td>Icing, one aircraft more than another</td>
<td>Aircraft have different aerodynamic loads and go at diff speeds</td>
<td>Moderate</td>
<td>Low</td>
<td>Don't fly in icing conditions</td>
</tr>
<tr>
<td>Aircraft control system failure</td>
<td>Aircraft cannot take desired position or leave the formation, possible collision</td>
<td>High</td>
<td>Moderate</td>
<td>Aircraft remove themselves from formation when anything fails</td>
</tr>
<tr>
<td>Some other aircraft system failure</td>
<td>Any of a number of things, including a possible collision</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Aircraft remove themselves from formation when anything fails</td>
</tr>
<tr>
<td>Common-mode control system failure</td>
<td>All aircraft lose control and have very high probability of collision</td>
<td>High</td>
<td>Low</td>
<td>Breakup strategy is robust to common errors</td>
</tr>
</tbody>
</table>
Certification Plan

• Software to DO-178B (Level A/B/C)
• Minimize intrusion/changes into existing avionics
• Certifiability
  – Early FAA consultation critical
  – Testable
  – Predictable
  – Redundant