Technology Considerations for Advanced Formation Flight Systems

Prof. R. John Hansman

*MIT International Center for Air Transportation*
How Can Technologies Impact System Concept

• **Need (Technology Pull)**
  - Technologies can fulfill need or requirement
  - Technologies can overcome barriers (limitations, constraints, etc.)

• **Opportunity (Technology Push)**
  - Technologies can Create Opportunities
  - New Capabilities
  - Competitive advantage
    - Cost
    - Performance
    - Maintenance
    - Other
Formation System Concept is Itself a Technology

- **Needs**
  - Efficient Transport
    - Fuel
    - Cost
      - Crew, Maintenance...
    - Operational Access (Noise, Runways)
    - Flexibility
    - Others

- **Opportunity**
  - Different design space if use multiple vehicles
  - Overcome constraints (eg runway width, single departure point)
  - Performance
    - Fuel efficiency, crew
  - Development of key technologies enable formation flight
  - Flexibility
  - Runway Throughput
What are the Key Technologies for Formation Flight

- Start with Fundamental Abstraction of System or Concept (many ways)
  - Functional
  - Operational
    - Concept of Operations
  - Physical
  - Component
  - Constraint
  - Information

- Based on Abstract view, identify
  - Technology needs
  - Key questions
  - Potential opportunities

- Useful to sketch elements to visualize system
  - Multiple views
What are the Key Technologies for Formation Flight
What are the Key Technologies for Formation Flight

- **Overall Concept Questions**
  - Concept of Operations?
  - How does form up occur
  - Station keeping requirements
  - Failure Modes
  - Existing elements or New
    - Vehicles
    - Control Systems
    - CNS
    - Other

- **Concept Scale Opportunities/Costs**
  - Performance gains estimate
    - Fuel
    - Capacity
  - Costs
    - Development
    - Deployment

- **Concept Technologies Reqs**
  - Formation design
  - Station Keeping
    - Com
    - Nav
    - Surveillance
    - Control
What are the Key Technologies for Formation Flight

- Communications
- Navigation
- Surveillance
- Control (Station Keeping)
  - Intent States
  - String Stability
- Vehicle Configuration
  - Aero/Performance
  - Control
- Propulsion
- Degree of Autonomy
- Flight Criticality
  - Hardware
  - Software
- Low Observability
- Others?
Communications

• **Requirements**
  - Communicate necessary information between formation elements and command node (LAN and Air-Ground)
  - Bandwidth
  - Low-Observable?
  - Synchronous vs asynchronous

• **Constraints**
  - Spectrum
  - Antenna Location

• **Technologies**
  - Radio
    - UHF, VHF, MMW
  - Optical
    - Laser
  - Protocols
COMMUNICATION

• **Voice**
  - VHF (line of sight)
    - 118.0-135.0 Mhz
    - .025 spacing in US, 0.083 spacing in Europe
  - UHF
    - 230-400 Mhz (guess)
  - HF (over the horizon)
  - Optical (secure)

• **Datalink**
  - ACARS (VHF) - VDL Mode 2
  - VDL Modes 3 and 4 (split voice and data)
  - HF Datalink (China and Selcal)

• **Geosynchronous (Inmarsatt)**
  - Antenna Requirements

• **LEO and MEO Networks**

• **Software Radios**

• **Antenna Requirements**
Generic Avionic System

- Antenna Sensor
- Black Box
  - Hardware
  - Software
- Interface Unit
  - Display MFD
  - Input Device
- Databus
- Antenna
- Datalink
- Flight Data Recorder
- Power
- Cooling
Navigation
(relates to Surveillance)

- **Requirements**
  - General Navigation (medium precision)
  - Station Keeping (high precision)
  - Integrity
  - Availability

- **Constraints**
  - Existing nav systems
  - Loss of signal

- **Technologies**
  - GPS/Galileo (need Differential)
    - Code vs Carrier Phase Approaches
  - IRS/GPS
  - Sensor Based Approaches for Station Keeping
    - Image (Visible, IR)
    - Range Finders (Laser, Ultrasonic)
The Global Positioning System
Measurements of code-phase arrival times from at least four satellites are used to estimate four quantities: position in three dimensions (X, Y, Z) and GPS time (T).

(Courtesy of Peter Dana. Used with permission.)

From http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html
Inertial Reference Unit

- Integrate acceleration from known position and velocity
  - Velocity
  - Position

- Need Heading
  - Gyros
    - Mechanical
    - Laser

- Can get Attitude
  - Artificial Horizon (PFD. HUD)

- Drift Errors
  - IRU unusable in vertical direction (need baro alt)
  - Inflight Correction
    - DME
    - GPS
    - Star Sighting for Space Vehicles

- Measurement Give Attitude Also

- 777 Analytical Redundancy
Surveillance

• Requirements
  - Observed states of lead elements sufficient to form-up and maintain station keeping either manually or by automatic control
  - Feed forward states (intent)

• Constraints
  - Sight Angles
  - Installation (weight, cost, power, etc)
  - Cooperative Targets

• Technologies
  - Automatic Dependant Surveillance Broadcast (ADS-B)
  - Image Based Systems (Vis, IR)
  - Radar (X Band, MMW0
  - Range Finders (Laser)
  - Sensor Fusion Systems
Bob Hilb
UPS/Cargo Airline Association

(Image removed due to copyright considerations.)
• **Wavelength** $\lambda$
  - $S$ Band (10 cm)
  - $X$ Band (3 cm)
  - $Ku$ Band (1 cm)
  - Millimeter Wave (94 Ghz pass band)

• **Radar Range Equation**

• **Beamwidth** $\Theta$
  - $\Theta = \frac{\lambda}{D}$
  - $D =$ Diameter of Circular Antenna
  - Pencil beam vs Fan Beam

• **Mechanically Steered Antennas**
  - Scan and Tilt
INTENT REPRESENTATION IN ATC

- Intent formalized in “Surveillance State Vector”

Surveillance State Vector, $X(t)$ =

- Traditional dynamic states
  - Position states, $P(t)$
  - Velocity states, $V(t)$
  - Acceleration states, $A(t)$

- Defined intent states
  - Current target states, $C(t)$
  - Planned trajectory states, $T(t)$
  - Destination states, $D(t)$

- Accurately mimics intent communication & execution in ATC
• Allows visualization of different (actual or hypothetical) surveillance environments

☐ Useful for conformance monitoring analyses of impact of surveillance
• Potential access to more states (e.g. dynamic and intent)
• Need to assess benefits for conformance monitoring
Control

- **Requirements**
  - Maintain Station Keeping sufficient to achieve formation benefits
  - Tolerance to Environmental Disturbances
  - String stability

- **Constraints**
  - Certification
  - Failure modes
  - Available states

- **Technologies**
  - Performance seeking control
  - Multi-Agent Control Architectures
  - Distributed Control Approaches
  - Leader-Follower Schemes
  - Fault Tolerant Systems
    - Redundancy Architectures
Automation

- **Requirements**
  - Form up and station keeping may need to be automated

- **Constraints**
  - Reliability, integrity
  - Certification
  - Failure Modes

- **Technologies**
  - Flight Directors
  - Autopilots
  - Intercept systems
• **Requirements**
  - High Integrity Implementation for Formation
  - Formation requirement exceeds specs for current vehicles (eg 777)

• **Constraints**
  - Failure Modes

• **Technologies**
  - DO 178B
  - ??
Aero-Configuration

- **Requirements**
  - Mission based requirements (you will define)
  - Formation based requirements
  - Special Control Requirements

- **Constraints**
  - Stability and Control (CG)
  - Formation and non-Formation operation

- **Technologies**
  - Conventional approaches modified by formation considerations
    - Asymmetric
    - Formation optimal vs single optimal
      - Lead - High WL, Low AR >> high vortex
      - Trail - Low WS, High AR >> Low drag
  - Vortex Tailoring
  - Unique configurations or control systems
• Symmetric vs Asymmetric

• Variable
  □ Formation vs Free Configurations

• Formation Specific Considerations
  □ What is the optimal aspect ratio for overall performance

• Are there special, non-classical control needs?

• What are takeoff and landing considerations

• In-flight physical hookups
Propulsion

- **Requirements**
  - Take-off, balanced field length >> drives thrust
  - Cruise efficiency
  - Response time

- **Constraints**
  - Operational in formation and non formation configuration

- **Technologies**
  - Unmatched multi engines (shut down in cruise, eg Voyager)
  - Broad operating envelope engines (SFC hit)
  - Tow Schemes
Voyager aircraft return from non-stop trip around the world

Voyager
Formation Transport Example:
C-47 (DC-3) towing CG-4 Cargo Gliders

Courtesy of the Atterbury-Bakalar Air Museum. Used with permission.

http://www.atterburybakalarairmuseum.org/CG4A_C47_color_photo.jpg
What are the risk considerations for technology incorporation

- **Readiness**
  - NASA Technology Readiness Levels (TRL)

- **Vulnerability**
  - High (Key Element on Which Concept Based)
  - Medium (Performance or Capability Enhancing, Competitive Factor)
  - Low (alternatives available)

- **Competitive Risk**
  - Goes both ways

- **Certification Risk**

- **Operational Considerations**
  - Issues are discovered in field operations
    - Tracking Programs
  - Unanticipated uses of technology
What are the risk considerations for technology incorporation

- **Readiness**
  - NASA Technology Readiness Levels (TRL)

- **Vulnerability**
  - High (Key Element on Which Concept Based)
  - Medium (Performance or Capability Enhancing, Competitive Factor)
  - Low (alternatives available)

- **Competitive Risk**
  - Goes both ways

- **Certification Risk**

- **Operational Considerations**
  - Issues are discovered in field operations
    - Tracking Programs
  - Unanticipated uses of technology