LESSONS LEARNED DURING DEVELOPMENTAL TEST OF THE X-47B AIRCRAFT

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First Flight Video

U.S. Navy X-47B Unmanned Combat Air System First Flight

Edwards AFB, Calif.
Feb. 4, 2011

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## UCAS-D Air Vehicle System (X-47B) in Focus

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td>Tailless, cranked-kite</td>
</tr>
<tr>
<td><strong>Plan form</strong></td>
<td>LO relevant features</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>Carrier approved</td>
</tr>
<tr>
<td><strong>Take-off gross weight (demo)</strong></td>
<td>44,000 lbs</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>PW F100-PW-220U</td>
</tr>
<tr>
<td><strong>Twin Internal Weapons Bays</strong></td>
<td>4,500 lbs payload</td>
</tr>
<tr>
<td><strong>Aerial refueling provisions</strong></td>
<td>USN / USAF style</td>
</tr>
<tr>
<td><strong>CV launch OPWOD</strong></td>
<td>+2.2 knots</td>
</tr>
<tr>
<td><strong>CV recovery WOD</strong></td>
<td>+7.2 knots</td>
</tr>
<tr>
<td><strong>Spot factor (F/A-18C)</strong></td>
<td>0.87</td>
</tr>
</tbody>
</table>
System Description – Design Features

Carrier Suitable System
- Strength, Durability, and Damage Tolerance to NAVAIR Requirements
- Carrier Suitable Vehicle Management and Flight Control System
- Carrier Suitable Performance and Flying Qualities

LO relevant design

Launch Bar
Tailhook
Carrier Suitable Landing Gear
UCAS Demonstration Objectives

• Demonstrate critical technologies for a Carrier Suitable, Low Observable (LO) Unmanned Air System in a relevant CVN environment (TRL-6)
  - Carrier Control Area (CCA) Operations
  - Catapult Launch and Departure Performance
  - Arrested Landing Performance Including Approach, Wave off and Bolter
  - Mission Control Segment (MCS) CVN Integration
  - UCAS interface to CVN and associated systems

• Critical Technologies include:
  - Autonomous CV/Tanker Airspace Ops
  - Guidance/Navigation/Control
  - Flush Air Data Systems
  - Tailless Vehicle Aero/Control
  - Low Latency Safety of Flight C2
  - Precision Navigation in CCZ
  - Deck Handling/Deck Operations

TRL - 3
Lab Testing C-12 & F/A-18 Surrogate Testing
Airworthiness Suitability Testing
Shore-Based Ship Area Testing
Carrier Control Sea-Trials

TRL - 6
Test Program Scope & Buildup

- Extensive Shore-based Lab Integration, M&S
- X-47B VMS Surrogate Flight Test
  - Vehicle Management System
  - MCS Integration
- A/SI Surrogate Flight Test
  - CV Segment Verification
  - Shipboard TTNT, PGPS Testing
  - CCA Operations
  - Approach, Bolter, Wave off, Departure
- Surrogate Shore Launches
  - CV Segment Verification
  - Shipboard TTNT, PGPS Testing
  - Shipboard MCS Testing
  - CCA Operations
  - Approaches, Touch and Go’s
  - Nominal & Off-nominal Tests
- Airworthiness/Envelope Expansion
- Shore-based Ship Suitability Tests
  - Catapult Launch, Arrested Landing
  - Deck Handling
  - Landing System Tests
  - Simulated CCA Operations
  - E3 Testing for CV Environment
  - Hoist Aboard
- UCAS Shore Launches
  - CCA Operations
  - Approaches, Touch and Go’s
  - Build down to first trap
- UCAS CVN Operations
  - Deck Operations, Catapult Launch, Departure, CCA Ops, Approach, Trap, Wave off, Bolter
X-47B Block 1 Edwards AFB

- Taxi, airworthiness testing
- Command and control data link verification
- Ground handling
- Navigation performance

- Airworthiness
- Flying qualities
- Approach and landing performance
Surrogate Aircraft Testing

• Manned surrogate testing used to mature and validate critical technologies for the UCAS demo
  – King Air, Lear Jet, F/A-18D, and K707 Tanker aircraft modified with UCAS hardware and software
  – Several aircraft carriers modified with the systems to support UCAS operations for the demo program

• Aircraft Carrier Systems surrogate testing
  – USS HARRY S. TRUMAN (CVN-75) test detachment in February 2010
  – USS DWIGHT D. EISENHOWER (CVN-69) test detachment in July 2011

• Autonomous Aerial Refueling surrogate testing
  – Niagara falls test detachment in October 2010
  – Upcoming test detachment in St. Augustine Dec 2011
Overview of Test Results to Date

- Hundreds of hours of on-aircraft Systems Check Out (SCO) and VMS 0015 check out
- Dozens of tow tests – now a standard maintenance evolution
- Full EMC/SOF evaluation of the Edwards AFB environment
- Over 100 mission rehearsals, simulator sessions, etc
- Over 100 Low, Medium and High Speed Taxi test events
- 18 Flights on the X-47B
- Hundreds of flight hours across 4 manned surrogate aircraft
X-47B Test Flight Route

Gear Down, 29 minutes total time en route
X-47B Flight 1-5 Highlights

- Testing accomplished:
  - 140 -180 KCAS in PA configuration, 160 - 180 in TO configuration at 5,000 and 7,500 ft
  - Pitch/Yaw/Roll doublets, steady heading sideslips, throttle burst and chop

- Nominal performance during all three flights
  - Cross track error, altitude error, and air speed control were very precise

- Acceptable Air Data System performance
  - Flush Air Data System, no flight test boom

- No system failures or faults

- Excellent touchdown dispersion and braking results

- RTB on Flight 3 due to indicated structural wing bending load measurement exceeding limit during final sideslip maneuver
  - Post test analysis indicated strain gage drift and no limit was exceeded
  - Effective drill for the test team!
Surrogate Testing Highlights

• Completed initial field performance testing of the UCAS carrier landing systems
  – Precision (Differential) GPS guidance using high speed data-link (Tactical Targeting Network Technology (TTNT))
  – Straight-in (Case 3) and approach turn (Case 1) automatic (coupled) landings
  – Field results were nominal with acceptable performance to test at CV at sea.

• Completed initial at-sea testing using surrogate aircraft on CVN-69
  – Build up approach – manual then automatic approaches
  – Completed first ever coupled arrestments to an aircraft carrier using GPS only guidance
  – Completed first ever coupled landings and arrestments in a Case 1 (approach turn) pattern to an aircraft carrier
First coupled arrestment
LESSONS LEARNED
Lesson Re-Learned #1
Software, Software, Software

- Airplane built and ready to fly/test on schedule, however, well ahead of software certification readiness
  - Over 2.5M executable lines of code

- V&V takes longer than anticipated after fixes to address discoveries

- Lab/Hardware In The Loop (HITL) testing is critical and can be a choke point
  - Program Action Request (PAR) burn down rate was affected
  - Manpower can be a limiting factor; 24/7 operations at times
Lesson Re-Learned #2A
Autonomous requires mindset change

- Contingency logic / fault response
  - Coding a machine to “react” like a human
  - Need to think of all “what-ifs” ahead of time and code responses
    - Challenge in early development and “unknown unknowns”
    - The desired Autonomous response could be different from what you would want from a manned air vehicle
  - Predictable response / unintended consequences validation
Lessons Re-Learned #2A (cont)
Autonomous requires mindset change

• Contingencies
  - Flight Critical Fault – “It depends”
    • Come back early or have separate profiles for different locations
      - Minimize time aloft
      - Or allow time to deal with emergency
  - Lost Link
    • Have to plan all contingency routing
    • Set Link timers to allow momentary interruptions / regain backup comms
      - Can’t be too long in case of other emergency
      - Risk of manually overriding planned flight route with an invalidated comm. configuration
  - General philosophy for contingencies
    • Decide, plan, code for all contingencies on ground
    • Allow AV to execute planned responses and monitor to ensure appropriate
    • **Override as a last ditch if necessary / undesired response**
    • Train for likely contingency scenarios prior to test flights
Lesson Re-Learned #2B
Autonomous requires mindset change

- Flight test maneuvers
  - Developed using standard FTM procedures for airworthiness
    - Multiple conditions and parameters for each condition
      - Coding many combinations for a “menu” of options that can be executed
      - Significant amount of time/effort to validate all maneuvers in simulation
    - FTMs have build up required, so key parameters need to be monitored/instrumented
      - FTE / RE involvement in development and expansion plan
      - Robust test planning
  - No way to change responses airborne or without a software change
    - Significant up front work and planning
    - Anything missed will have to be re-coded or reduced in scope
  - Maneuvers are precise -- minimizes re-fly potential for missed / blown points
Which of These Data Sets is Actual?

- Data plots from flight number 2 versus simulation results

<table>
<thead>
<tr>
<th>BLUE=Simulation</th>
<th>RED=Flight test data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch rate</td>
<td>Time</td>
</tr>
<tr>
<td>Roll Rate</td>
<td>Time</td>
</tr>
<tr>
<td>Yaw Rate</td>
<td>Time</td>
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</tbody>
</table>

- Very close correlation between predicted results and observed results

- Builds confidence in performance of system under test
Lesson Re-Learned #3
Good Crew Resource Management Critical

• Low speed taxi tests
  - Taxi Test 2
    • Breakdown in communications
      - Cleared for a block of steps, difficulty with radio transmissions
      - Procedural error not caught
    • Only one of the “holes” in the Swiss cheese model
      - Incorrect interpretation/implementation of software requirement
      - Data review pacing test

• Lessons learned
  - Testing continues until the aircraft is secured
  - Plan, practice, then follow good comm discipline
  - Support/maintenance equipment and procedures are part of the “system under test”
Lessons Re-learned #3
Training, Training, Training

• Training as part of validation
  - Ran small test team rehearsals using pre-validated mission plans
    • Work out timing / discover issues / update profile prior to formal validation
    • Practice contingencies
  - Mission operators worked directly with coders to develop / validate plan

• Train nominal mission scenarios and contingencies with entire team
  - Goods
    • Work as a team to iron out solutions
    • Develop cards / procedures / workarounds
    • Identify new anomalies / limits
    • Expose entire team to off-nominals, develop contingency plans with experts
  - Others
    • Coordination logistics of team
    • Experience / background of engineers to practice “cockpit” ORM, SA, assertiveness
    • Decision by committee
Lessons Re-learned #4
Training, Training, Training (cont.)

• Team training highly successful
  – Successes
    • Aircrew (MOs) sit side by side with RE, TC, TD
      – Expose entire team to off-nominal, develop contingency plans with experts
      – Line of sight trust / discussion
      – Aircrew can “see” displays of RE if a question arises
    • On site resident expert who built/developed system
      – Living user manual
      – Work as a team to iron out solutions
      – Develop cards / procedures / workarounds
      – Identify new anomalies / limits
    • One to one training environment with RE/FTE/Aircrew
      – Train and fly in same control center
      – Enhances Crew Resource Management
Lesson Learned #3
Taxi Testing is not Straightforward or Easy

• High Speed taxi tests
  – High risk / a lot of planning discussion
    • Traditionally very low amount of HST done in manned aircraft
      – Verify control power, air data
    • For autonomous system, need to evaluate all of those items plus
      – Interlock response
      – Corrections, response to disturbances, during T/O and landing roll
      – Ground to aero control / braking transition
  • Balanced approach (how much risk is too much)
    – Initially desired 19 HST taxi runs
      » Concern over the risk/reward
      » HST runs essentially takeoff aborts
    – Reduced to 11 critical points
      » Still concern over amount
    – After braking anomaly (separate discussion), reduced to 4 runs
Braking Challenges

- Brake asymmetry
  - No differential braking
  - Asymmetric brake performance creates yaw disturbance
  - Slightly exceeded cross track error SOT limit
  - Saturated NWS control power
- Stop, evaluate
  - Software fix required significant software change / hardware change
  - Reduce contributing factors
    - Brake Control Valve (BCV) mismatch
      - Bring to within acceptable tolerance
      - Monitor
    - Build up in deceleration rate to determine acceptable rate to minimize
- Long term solution versus good enough
  - What is acceptable performance?
    - Characterize system based on design model
    - Update design model based on data
    - Determine if acceptable
  - Deemed okay to continue (at risk)
Lesson learned #6
Surrogates are not exactly like the test article

- Carrier landing systems field testing
  - Simulations do not always translate exactly to the aircraft hardware
    - Command/response polarity and magnitude
      - Initial response different from inputs
      - Smooth versus step response
  - Software coded for precise closed-loop aircraft path
    - Deviations from path at transition to automatic control caused unexpected guidance
    - Usually required airborne troubleshooting, decreasing test efficiency
  - Effects of Datum conversion on a GPS based system

- Testing at sea
  - Precision GPS guidance and satellite DOP
    - Plan events to minimize performance disruptions
    - Sometimes could not avoid due to real world constraints
## Upcoming Testing

<table>
<thead>
<tr>
<th>CV Suitability Testing</th>
<th>Launch and Recovery Bulletin (LRB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• EMI Testing</td>
<td>• Cat Steam Ingestion</td>
</tr>
<tr>
<td>• PA Flying Qualities</td>
<td>• Arresting Cable Roll-ins/Roll Over</td>
</tr>
<tr>
<td>• Loads Buildup (Cats/Traps)</td>
<td>• Jet Blast Deflector</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Carrier Control Area / Zone</th>
<th>Autonomous Aerial Refueling</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Land Launch – transit to OPAREA</td>
<td>• Rendezvous</td>
</tr>
<tr>
<td>• C2 Handoff</td>
<td>• Station Keeping</td>
</tr>
<tr>
<td>• Marshall / Holding</td>
<td>• Basket and Boom</td>
</tr>
<tr>
<td>• Case 1,2 and 3 approaches</td>
<td></td>
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<tr>
<td>• Deck Handling</td>
<td></td>
</tr>
<tr>
<td>• Traps and Cats</td>
<td></td>
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</tbody>
</table>
Summary

- Solid results to date from test aircraft and surrogates
- Modeling and simulation providing valuable insight
- Extensive team training paid off
- Lessons learned are being applied to ensure we have a safe, efficient, and executable test program
- Looking forward to providing update next year
Questions?
First Surrogate Coupled Trap