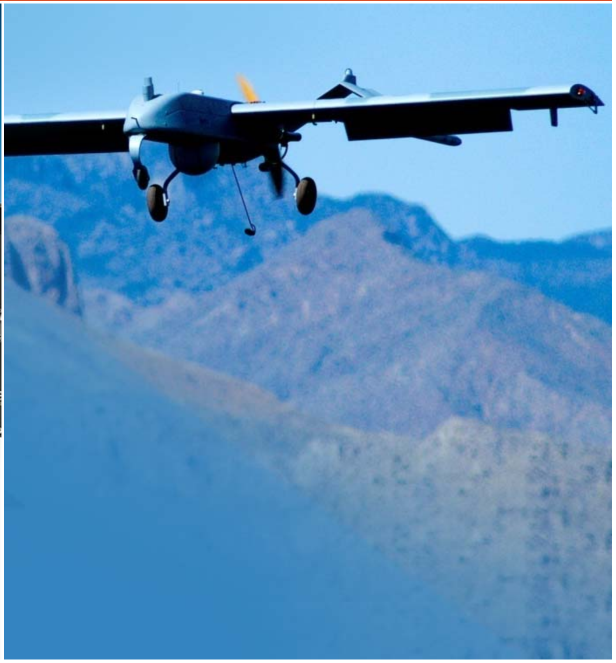


Damage Tolerant Flight Control Systems for Unmanned Aircraft

September 17, 2008
Vlad Gavrilets, Ph.D.

Approved for public release, distribution unlimited

Rockwell Collins Control Technologies - Formerly Athena Technologies

- Founded in 1998 and acquired by Rockwell Collins in April 2008, we invented, developed and brought to market new controls technology – which today is incorporated in the Athena product line of flight control and navigation systems
- Service military, experimental, general and business manned and unmanned aviation markets worldwide
- Full service provider – enabling customers to reduce time to market and program life cycle cost
- A few of our customers:

AAI Corporation's Shadow- US Army

Insitu's Scan Eagle Navy & Marine Corps

Alenia's Sky-X

Raytheon's Loiter Attack Munition

Textron Systems U-ADD

General Atomics' ER/MP Warrior

CEi's Air Force BQM-167A Target

EMT Luna

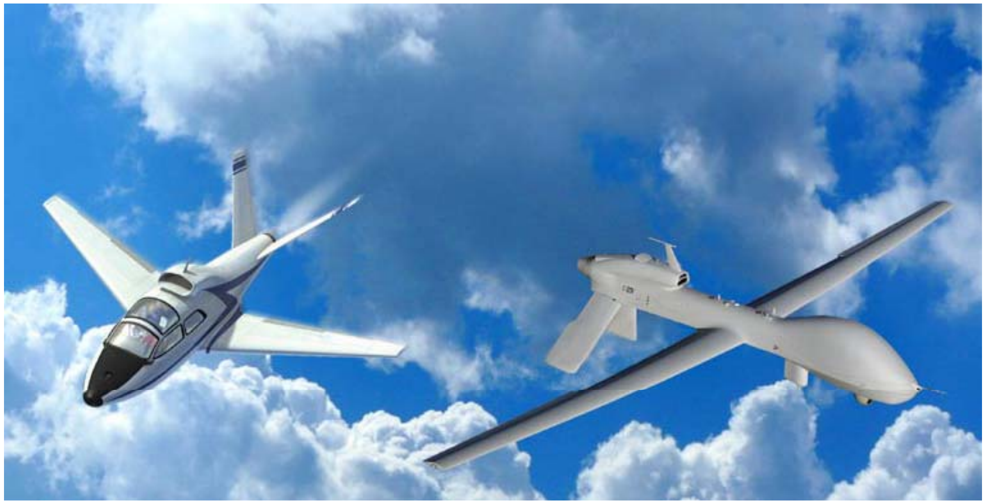
Aurora Flight Sciences OAV-II

Watchkeeper

The Problem: Damage and In-Flight Failure

Battle Damage Threatens Safety, and Security

Convergence of Manned & Unmanned Aircraft in Crowded Commercial Airspace



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The Solution: Technologies such as Damage / Fault Tolerance

Testing Platform: Subscale F / A-18 UAV

Subscale F/A-18 at Philips Army Airfield in Aberdeen, MD

Inset: Ejected aileron simulating battle damage

Athena 111m

Athena Flight Control and Navigation Systems

Damage Tolerance Phase I - 18-Apr 07

- Used subscale F/A-18 vehicle for demonstration
  - Turbo jet
  - Athena 111m
  - Fully autonomous operations: takeoff to landing
- Basic sequence
  - After takeoff and climb to altitude, right aileron intentionally released
  - Adaptive-control system automatically evaluates and recovers
  - System autoland

Timeline from Start to Production:
90 Days; 4 Full time people

Damage Tolerance Phase II – More Damage - Greater Risk

2 Flight Tests at Aberdeen – 22-April 08

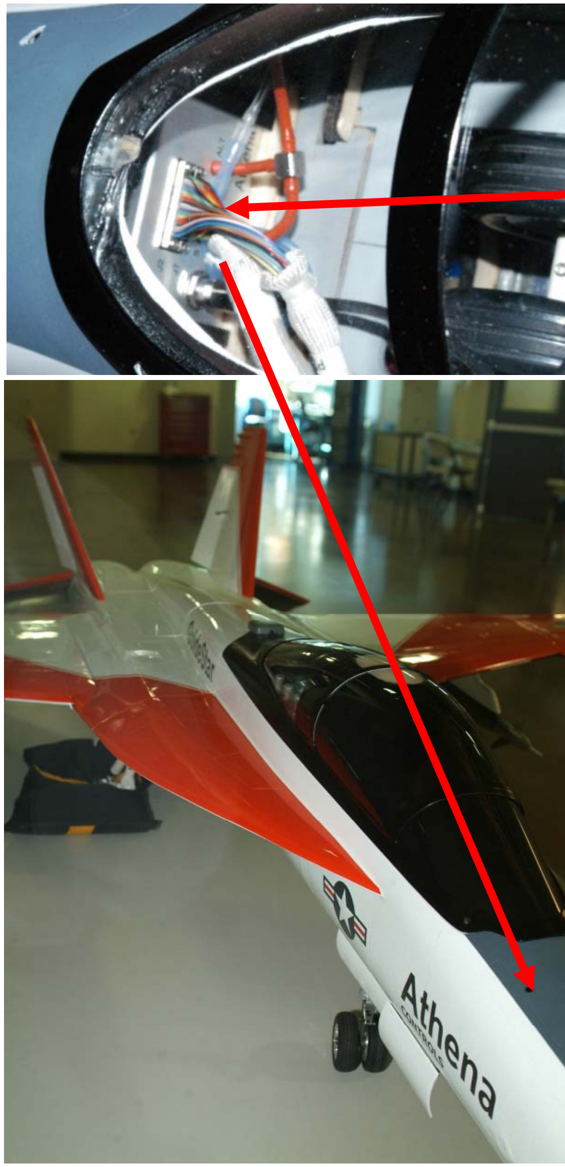
Basic sequence for both flights

- Auto take off and climb to altitude
- Ejection of 41% (area moment) of wing during1st flight
- Ejection of 60% (area moment) of wing during 2nd flight
- Introduced Automatic Supervisory Adaptive Control (ASAC) technology which reacted to new vehicle configuration
- Automatically regained baseline performance
- Continued to fly the plane
- System autoland using INS/GPS reference only

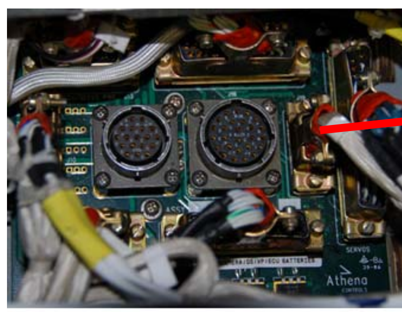
Flight 1 – 41% Wing Loss

Flight 2 – 60% Wing Loss

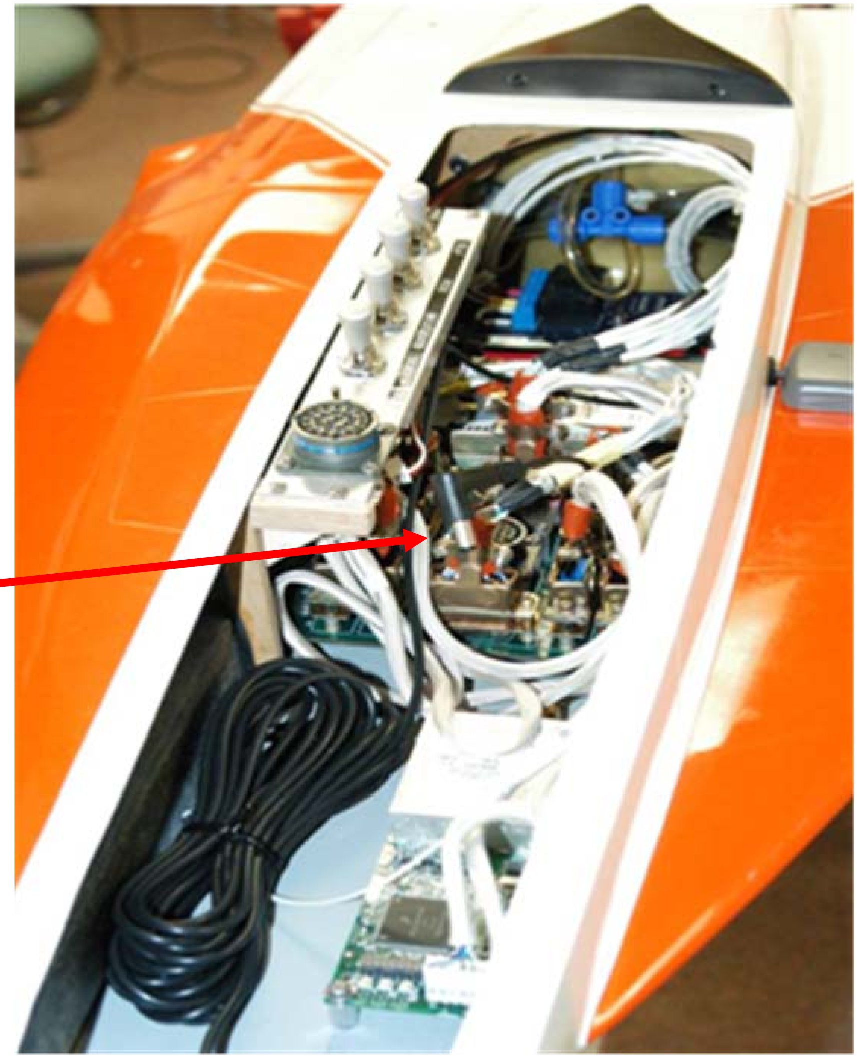
Hardware and Software



Athena 111m



Power Board installation



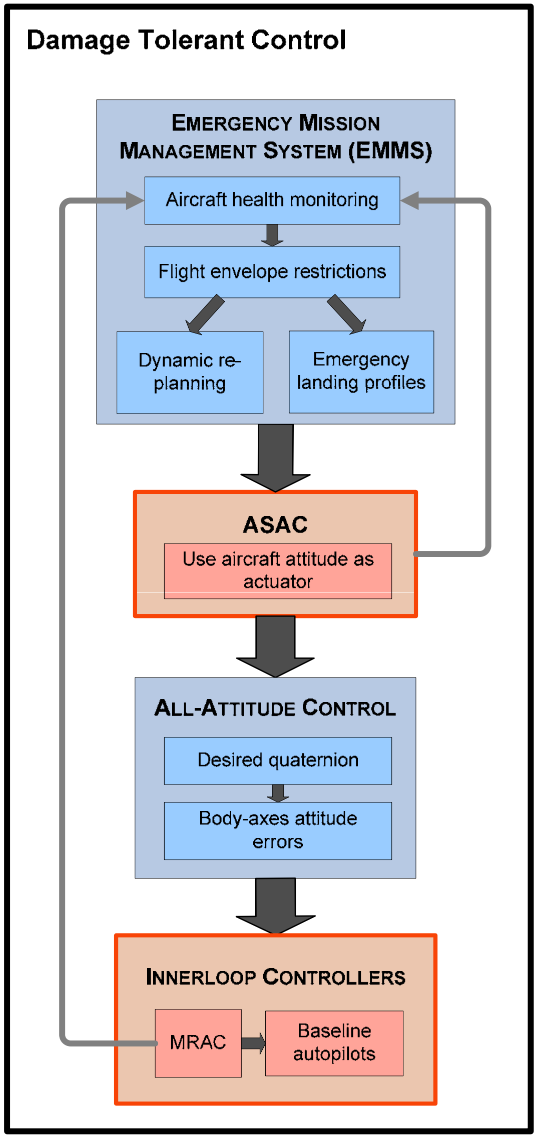
F/A-18 Avionics Bay

Damage Tolerant Control overview (1)

This block diagram shows the high-level architecture of RCCT's Damage Tolerant Control (DTC). Key technologies include:

- Emergency Mission Management System (EMMS)
- Automatic Supervisory Adaptive Control (ASAC)
- All-attitude controllers
- Model Reference Adaptive Control (MRAC)

ASAC and MRAC were demonstrated using RCCT's subscale F-18 UAV.



Damage Tolerant Control overview (2)

DTC core algorithms:

- Automatic Supervisory Adaptive Control (ASAC):

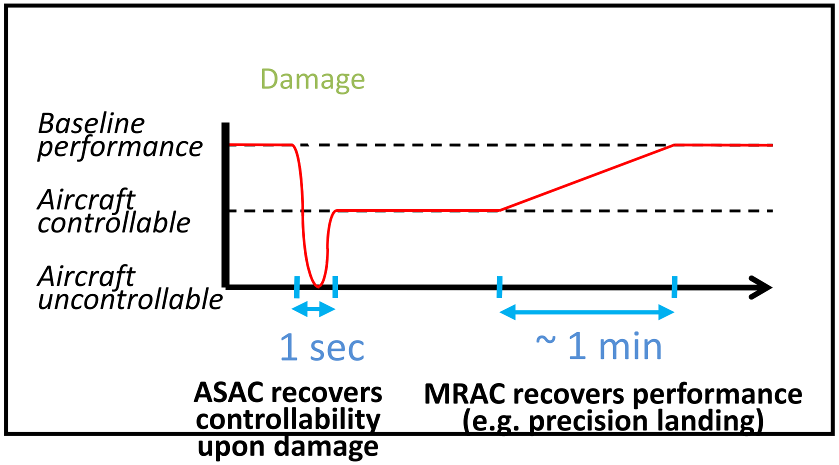
  The entire aircraft is used as an actuator by directly controlling the vehicle attitude with respect to the wing vector

  ➔ Return to trimmed and controlled flight

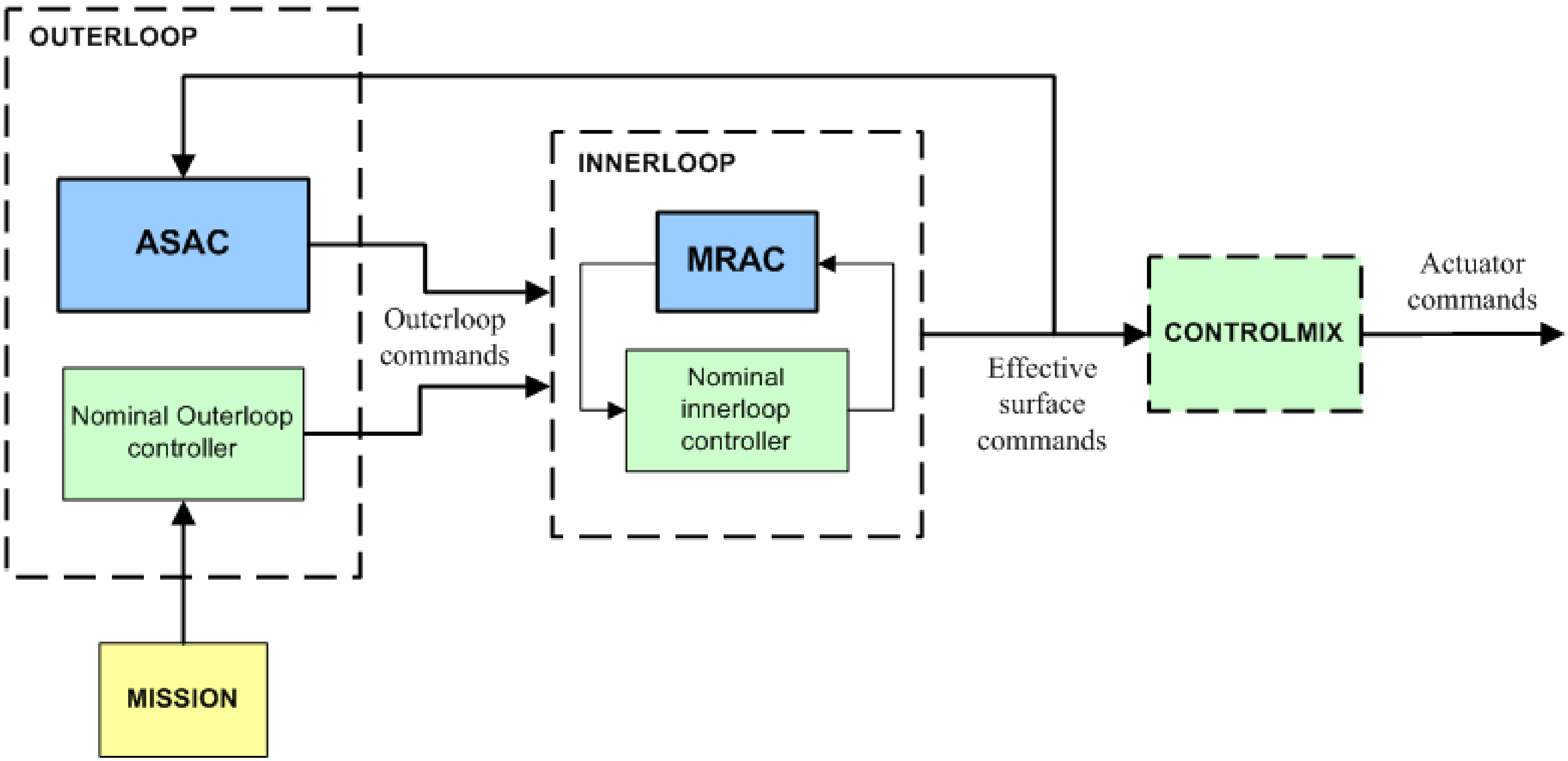
- Model Reference Adaptive Control (MRAC):

  The observed aircraft performance is compared to what it should be, and the autopilot gains are appropriately adapted

  ➔ Recover baseline performance

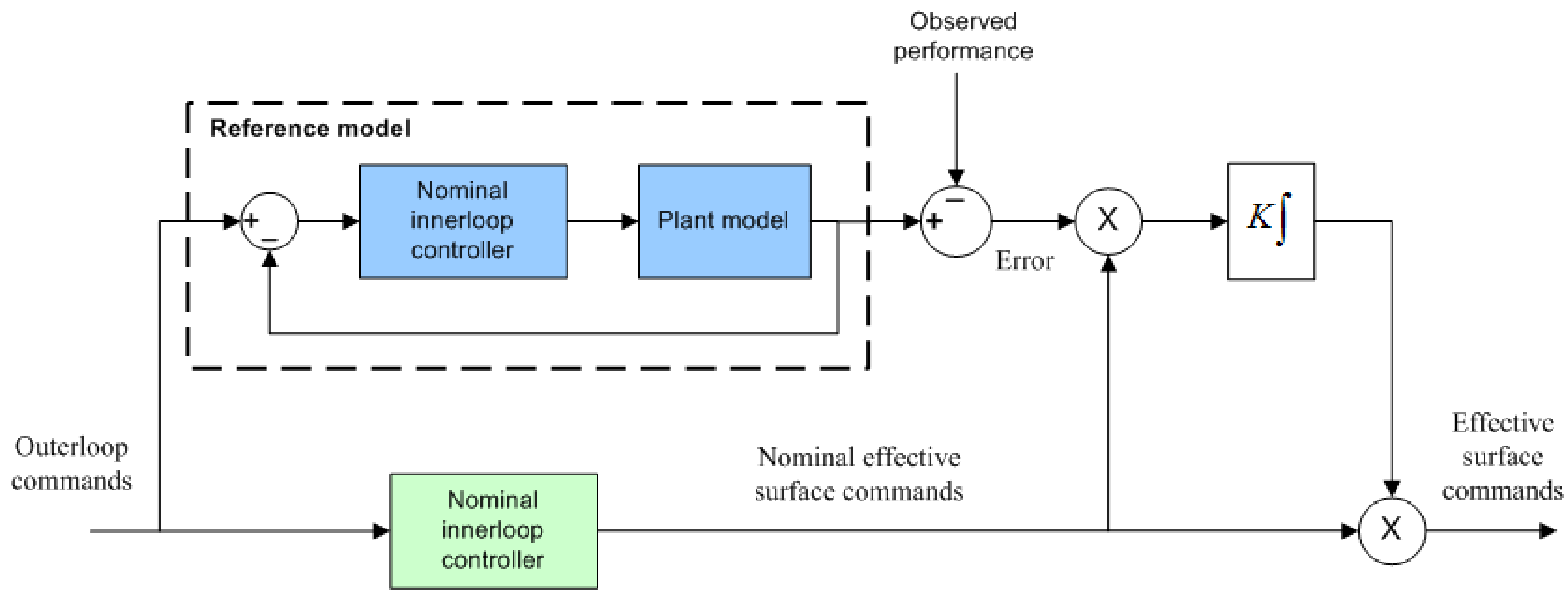


Damage Tolerant Control overview (3)



MRAC overview

- When an actuator is failed/damaged, MRAC increases the loop gain until the (observed) plant performance matches that of the original model
- Convergence guaranteed by Lyapunov stability theory
- Minimum vehicle-specific parameters for rapid deployment on a new platform
- Seamlessly blends into operational scenarios

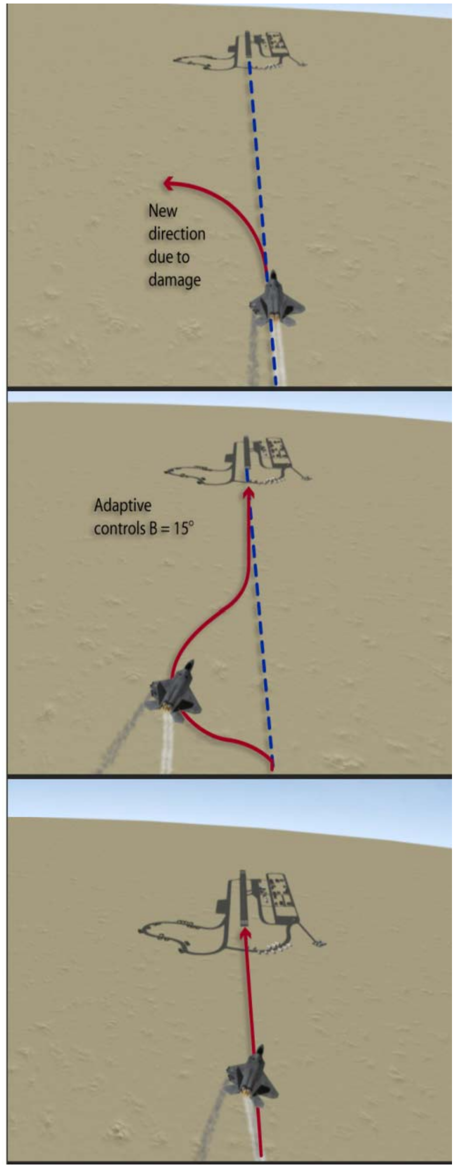


ASAC overview

Use the control surfaces and the orientation of the vehicle to achieve the desired trajectory and velocity vector.

Adapt the control of attitude to get to the desired trajectory:

- Use vehicle-specific characteristics to directly generate forces and moments from vehicle orientation
- Rapid response to damage for seamless recovery from damage
- Retain ability to perform autonomous landing with damage
- Maintain trajectory control with partially controllable platform



Flight results

Flight tests were performed with different wing damage:

Robustness of the algorithms:

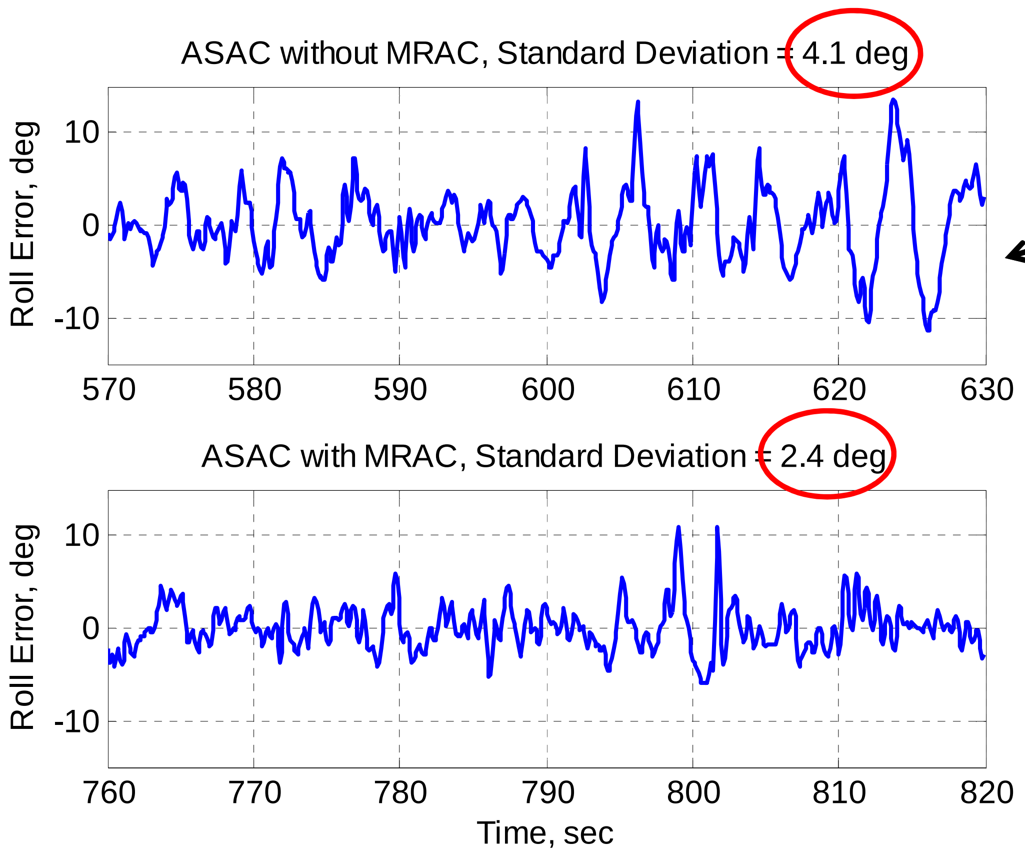
- right aileron stuck to neutral
- right aileron released
- right wing lost 40% of its area moment (+ right aileron)
- right wing lost 60% of its area moment (+ right aileron)

Results presented are from the 60% damage case, a fully autonomous flight from take-off to landing.

April 2008 flight test where the right wing lost 60% of its area moment

Flight results: MRAC

MRAC appropriately increased the innerloop gain by 40%, yielding a 40% improvement in roll tracking with damage.

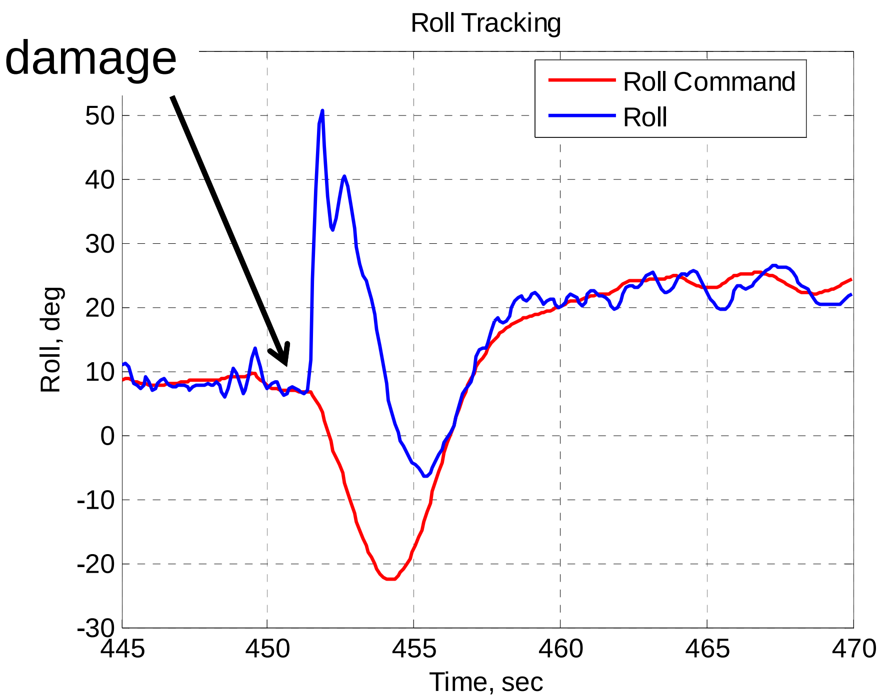


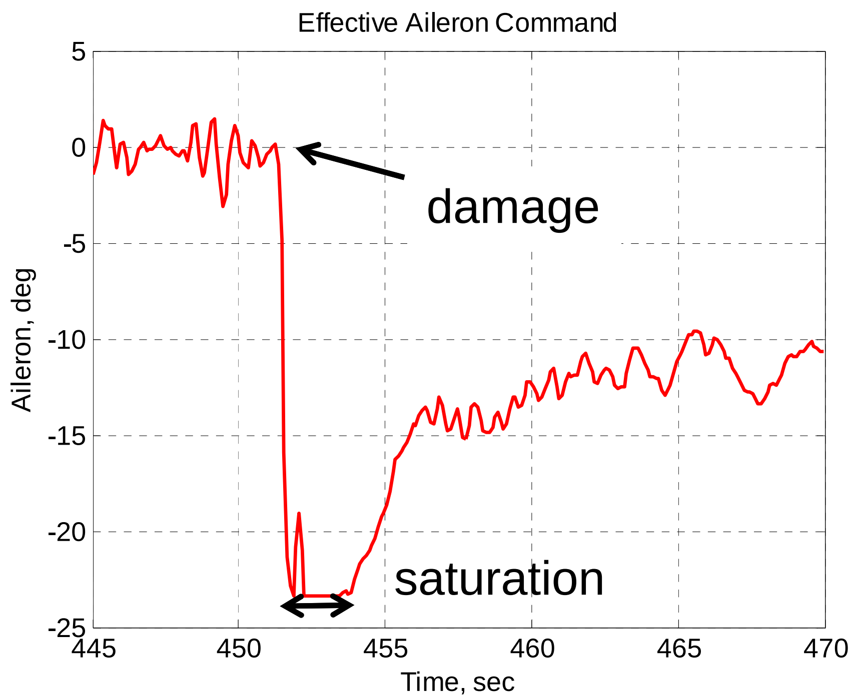
Roll tracking error of the damaged aircraft before MRAC

After MRAC

Flight results: ASAC (1)

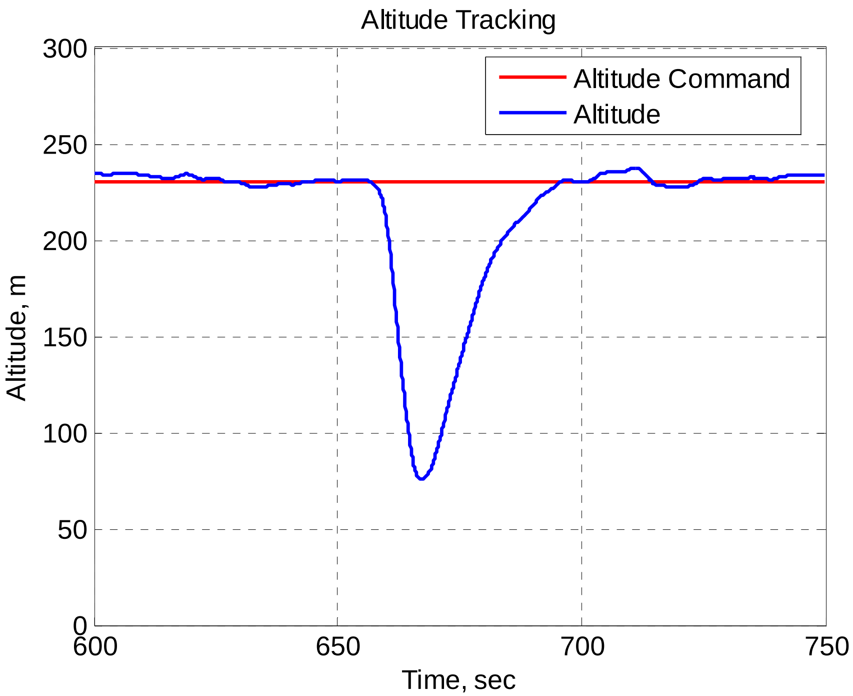
ASAC responded quickly to damage, relieving the saturation of the roll control surfaces

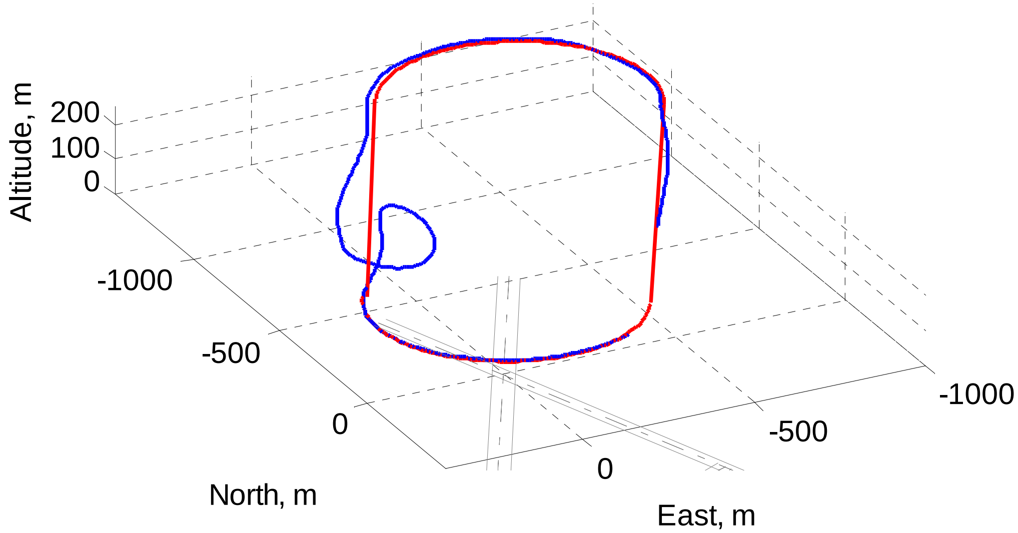


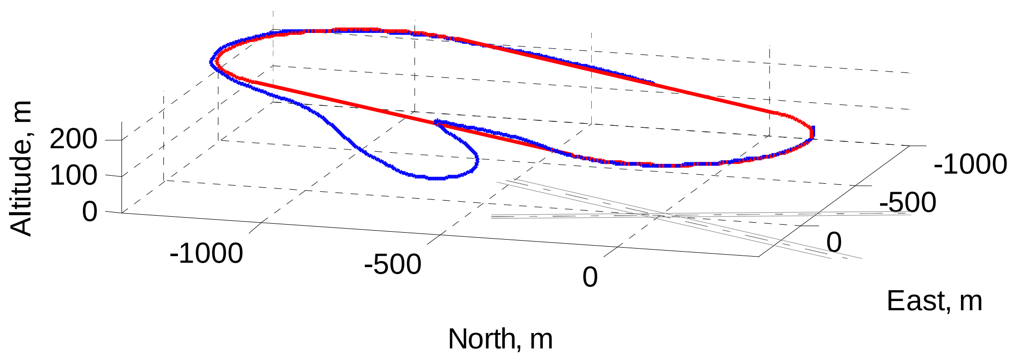


Flight results: ASAC disabled (1)

ASAC was briefly disabled to show that without it, the aircraft would crash.





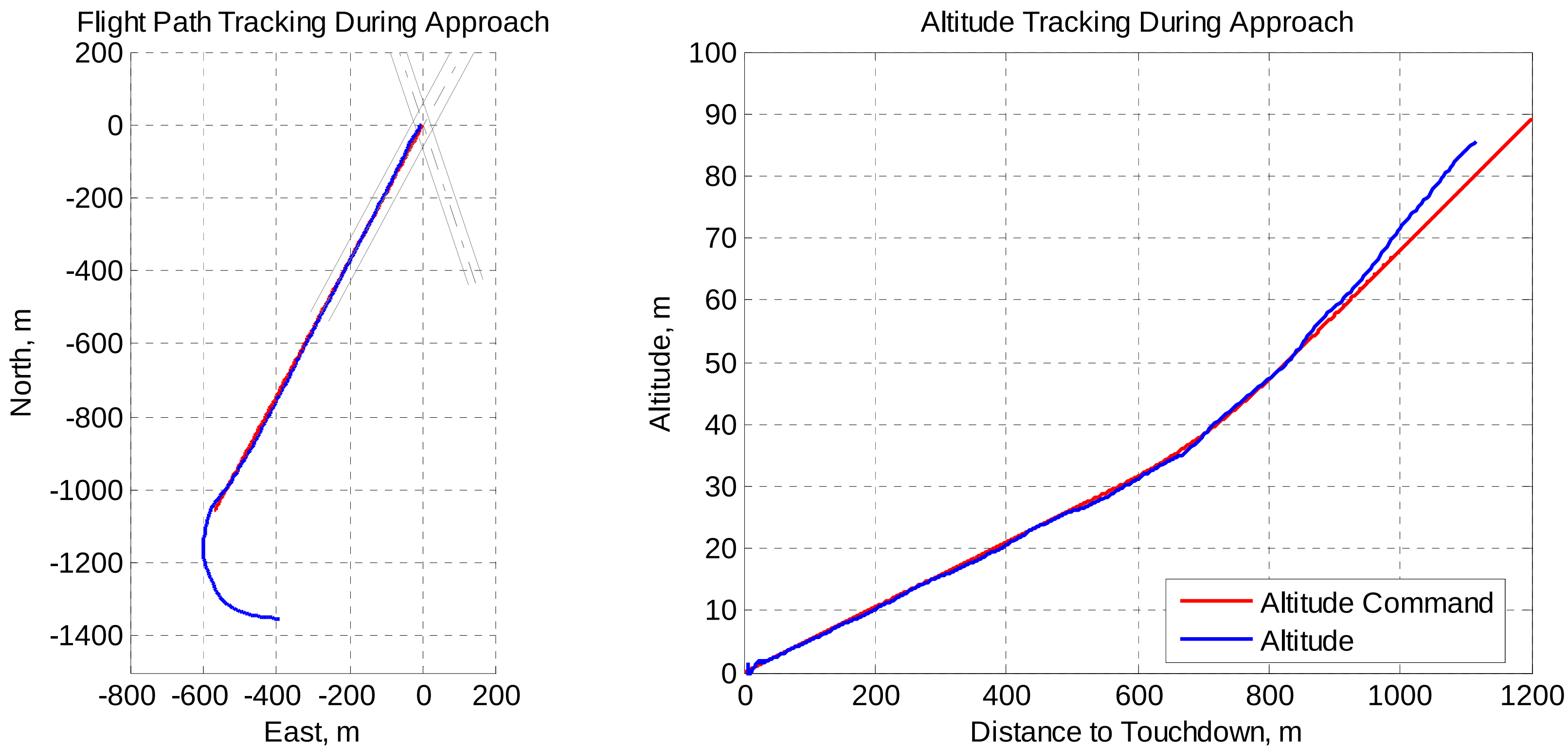


Flight results: ASAC disabled (2)

Onboard view when ASAC was disabled. Note the 90 deg bank angle (left) and the loss of altitude(right).

Flight results: Autoland (1)

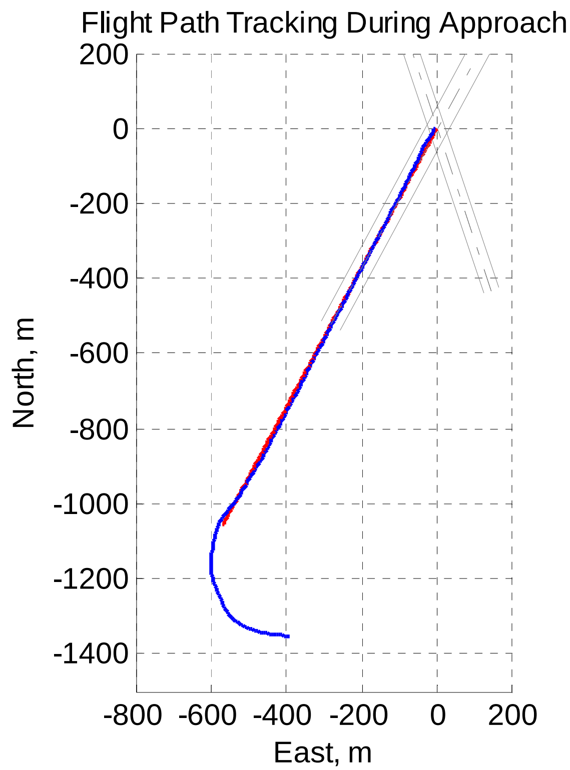
The aircraft completed its flight with a flawless autonomous landing.

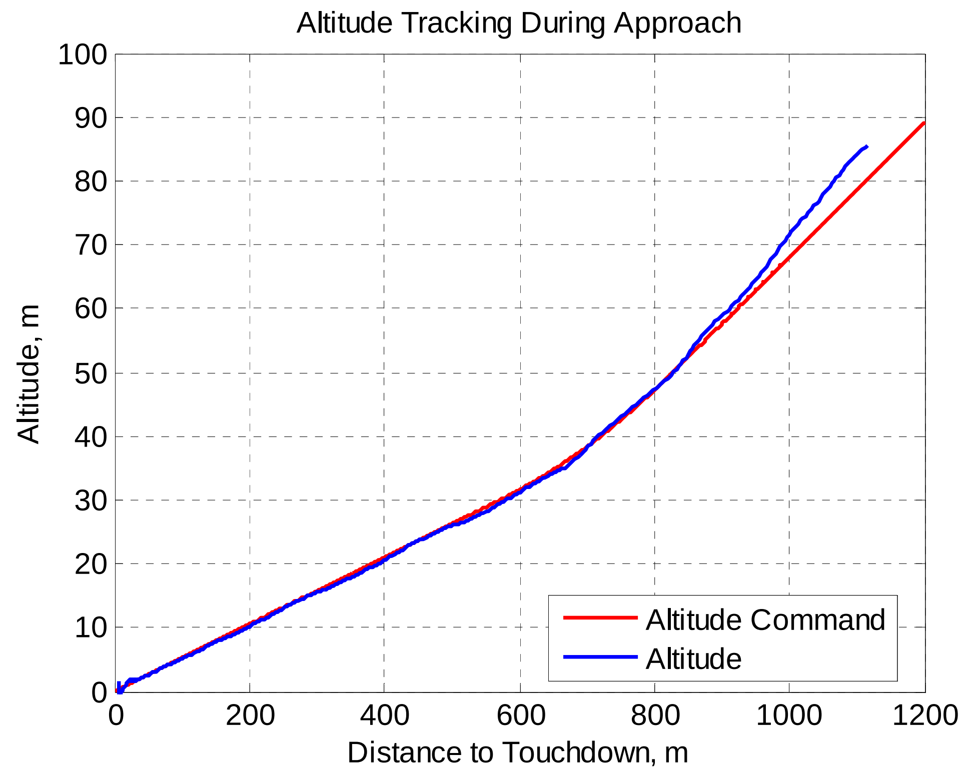


Views of the final approach at Phillips Army airfield, Aberdeen Proving Grounds, MD

Flight results: Autoland (1)

The aircraft completed its flight with a flawless autonomous landing.





Views of the final approach at Phillips Army airfield, Aberdeen Proving Grounds, MD

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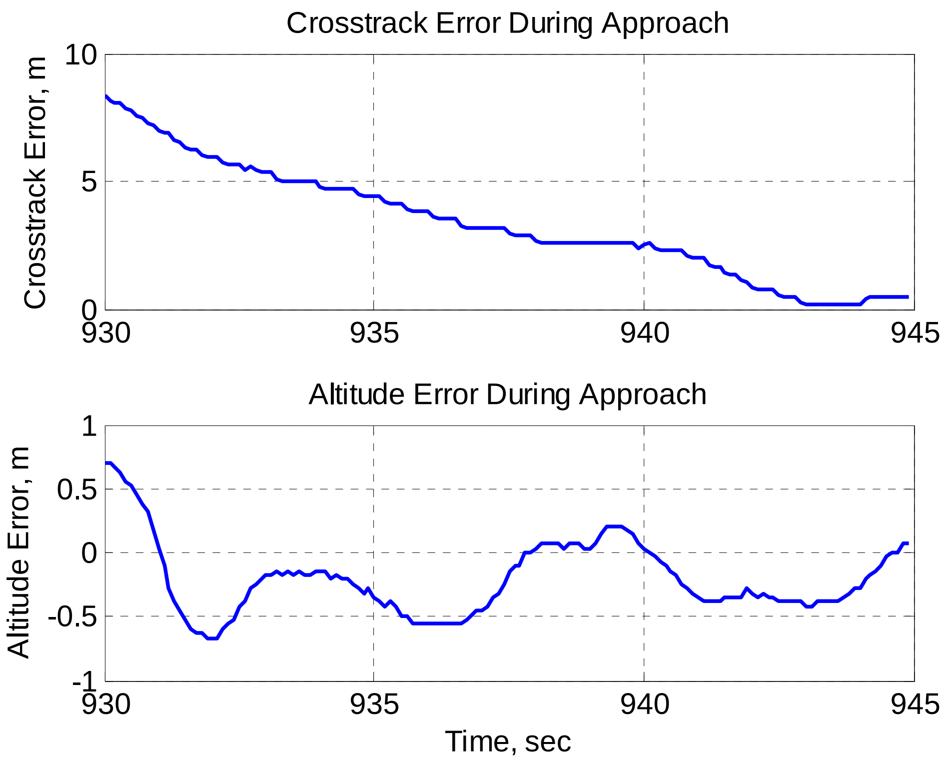
Flight results: Autoland (2)

In spite of 60% area moment loss on one wing and one aileron missing, the aircraft tracked the approach profile very accurately. The cross-track error quickly converges under 1m, and the altitude tracking error is under 1 foot RMS.



Cross-track (top) and altitude (bottom) errors during the final approach

Simulation results: Autoland

Monte Carlo simulations using RCCT's flight-proven 6-DOF nonlinear simulation environment were performed under different levels of wind, turbulence and damage. Statistics on touchdown for the subscale F/A-18 are shown below.

Damage	Survivability	RMS Roll at TD	RMS Pitch at TD	RMS Cross-track at TD	RMS Vertical velocity at TD
20%	100%	6.8 deg	5.8 deg	2.3 m	-1.4 m/s
30%	90%	8.7 deg	5.9 deg	3.8 m	-1.5 m/s

The Results

- Military Manned and Unmanned Aircraft
  - Ability to reduce loss of UAVs and manned aircraft in combat
  - Security of US sensitive technologies
  - Facilitates greater use of UAVs in high threat operations – saves lives and reduces costs
  - Combined with flight control redundancy; improves reliability exponentially
- Civilian Manned and Unmanned Aviation
  - Can be used on aircraft for fault tolerance
  - Can be used by pilots for upset recovery
  - Can be used by pilots and passengers for panic button autoland
  - Combined with Rockwell Collins sense and avoid technologies, provides complete solution and facilitates convergence of manned and unmanned aviation in commercial airspace

For more information, visit www.rockwellcollins.com or contact vgavrile@rockwellcollins.com