FLIGHT TEST METHODS FOR UNMANNED AIRCRAFT

SMALL UAV TESTING
HIGHLY AUTONOMOUS SYSTEMS

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40 Years of Flight Test Engineering
25 Years of UAS Flight Test Engineering

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10 Years of UAS Operational Experience
Groups 1-5 UAS Platforms

Agenda

- Small UAV Testing
  - Unique Challenges
  - Systems of Systems
  - Safety Considerations
  - Small UAV Test Program Management
  - Flying Qualities
  - Performance
  - Launch and Recovery
  - Human Factors
  - Survivability Testing

Agenda (Cont.)

- Highly Autonomous Systems (HAS)
  - Definition of “Autonomous”
  - Philosophy of Testing HAS
  - Fundamental Test Approach
  - Potential Problem Areas
  - UAS Swarms

Small UAV Testing

- Unique Challenges
  - Aerodynamic phenomena of small airframes
  - Instrumentation
  - Special Safety Considerations
  - Technological Variety
  - Commercial/ Commercial-Derivative Technology

Small UAV Testing

- Systems of Systems
  - Functionality offboarded from aircraft to external systems
    - Propulsion: Launch/Recovery Equipment
    - Navigation: Ground Control Station, DGPS
    - Data Dissemination: Ground Control Station
    - “Multisensor Platform” vs “Multiplatform Sensor”

Small UAV Testing

- Systems of Systems
  - Evaluate each component's contribution

Mission Thread: Aerial Reconnaissance								
	Receipt of Tasking	Planning/ Configuration	Launch/Recover	Transit	Target Search	Target Detection	Target Identification	Target Reporting
Human Operator	Poor radio contact			Hands-off automated transit				No radio contact
Ground Control Station		Cumbersome sensor planning				Low resolution; target was missed on first pass	Target identified at 800m slant range	
Launch/Recovery Equipment			Damage on recovery					
Air Vehicle				High HDOP caused drift off course	Executed planned search profile		Engine noise caused audible compromise	
Payload		Cumbersome sensor planning			Executed planned search profile	Low resolution; target was missed on first pass	Target identified at 800m slant range	
Remote Video Terminal							Target identified at 800m slant range	Unable to cue external consumer onto specific target
External Consumer	Poor radio contact							No radio contact

Small UAV Testing

- Safety Considerations
  - Lost Link Contingencies
    - Datalink Redundancy
    - GCS Redundancy
    - Lost Link Plan
  - Flyaway Mitigation
    - Flight Termination
    - Geofence
    - Indoor Testing
    - Tether
    - Limited Fuel/Battery

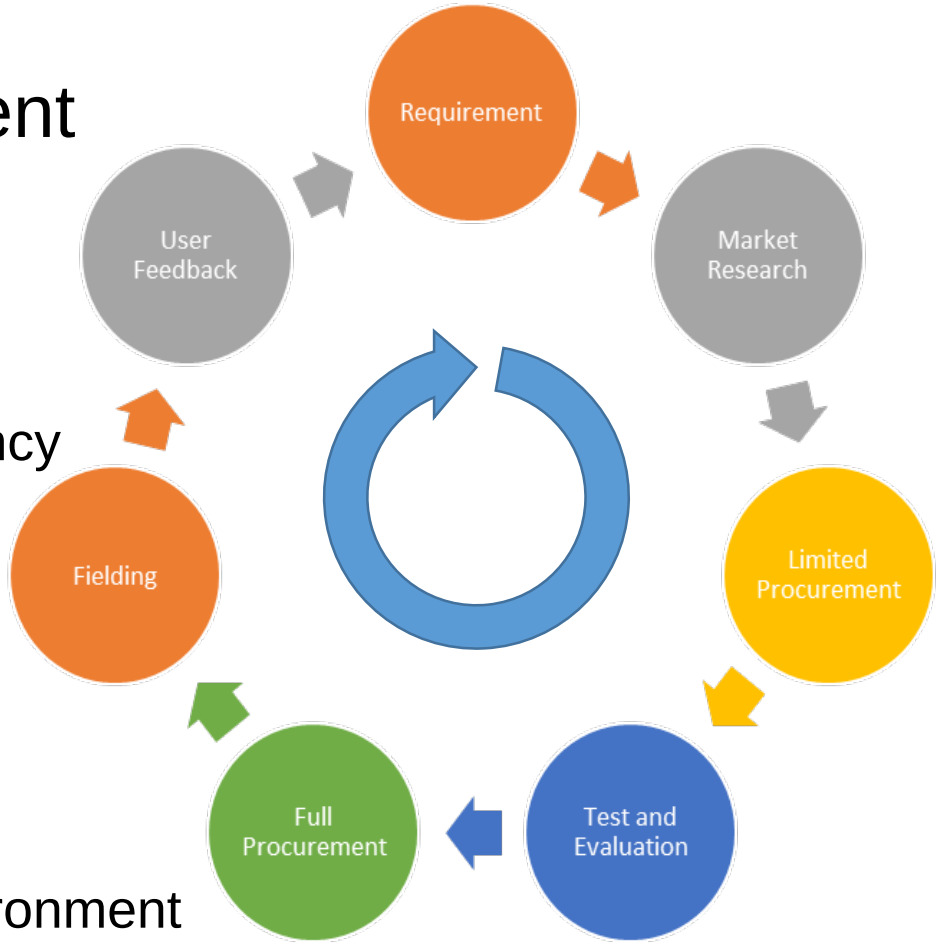
Risk Tolerance Paradigm Shift:
The UAV may be expendable, but people and property are not.

Small UAV Testing

- Test Program Management
  - “Speed to Field” vs “Test Rigor”
  - Short sortie duration
    - Test team efficiency!
  - Limited test budget
    - Test Budget vs Program Budget
  - Test *with* aviators
    - Risk Management
    - System Technical Characterization
  - Test *for* non-aviators
    - Human Factors
    - Tactics, Techniques, Procedures (TTPs) development
    - Final assessment from representative users

Small UAV Testing

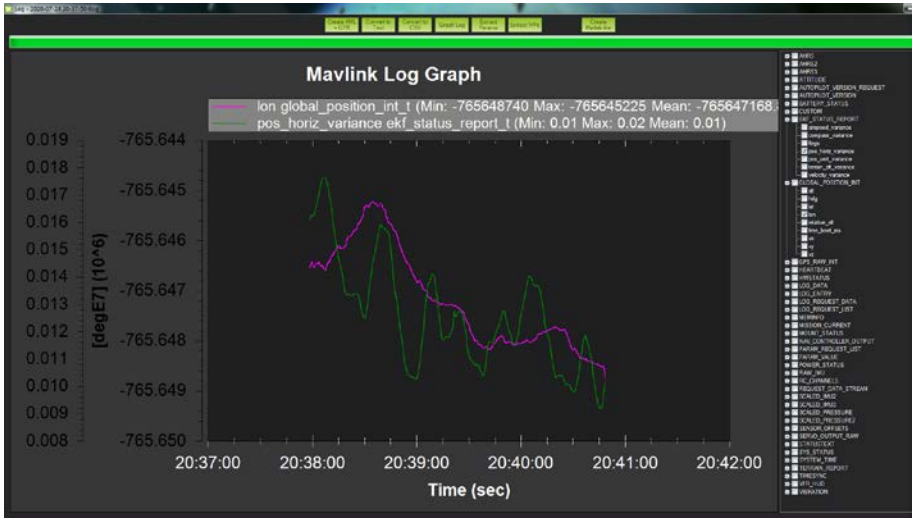
- Test Program Management
  - Increasing appetite for Commercial-off-the-Shelf (COTS)
    - Contractor Testing sufficiency
      - Flight Safety
      - Flying Qualities
      - Navigation/Control
      - Reliability
    - Reusable test metrics
      - MOP, MOE, MOS
    - Relevant Operational Environment
    - Mission Relation
    - Adequate Level of Test
      - “Minimum Sufficient”
      - “Limit of Practicality”



PURPOSE (SCOPE) OF TEST:
What questions are you answering?
What decisions are you supporting?

Small UAV Testing

- Flying Qualities
  - “Sticks”, “Waypoints”, “Follow Me” Flight Modes
  - Low Error Tolerance
  - Low Altitude Environmental Instability
    - “Brute Force” time-averaging
    - Bound flight envelope to operational concept
  - Instrumentation Challenges
    - Range Instrumentation Cost Practicality
    - “Orange Wire” SWaP
    - Telemetry Logs
    - Truth Data
  - Pilot Workload



Small UAV Testing

- Performance
  - Exotic propulsion methods not practical for manned aircraft
  - Unconventional airframe designs
  - “Fly-by-Output” control variety
  - Increasing levels of autopilot autonomy
  - Flight Mode transitions

Small UAV Testing

- Performance
  - Powerplant Diversity
    - Propeller/Rotor
    - Vectored Thrust
    - Ornithopter
    - Turbine Engine
    - Reciprocating Engine
    - Electric Motor
  - Energy Source Diversity
    - Jet Fuel
    - AVGAS
    - Hydrogen Cell
    - Propane
    - Chemical Battery
      - Li-Ion/LiPo
      - NiCad

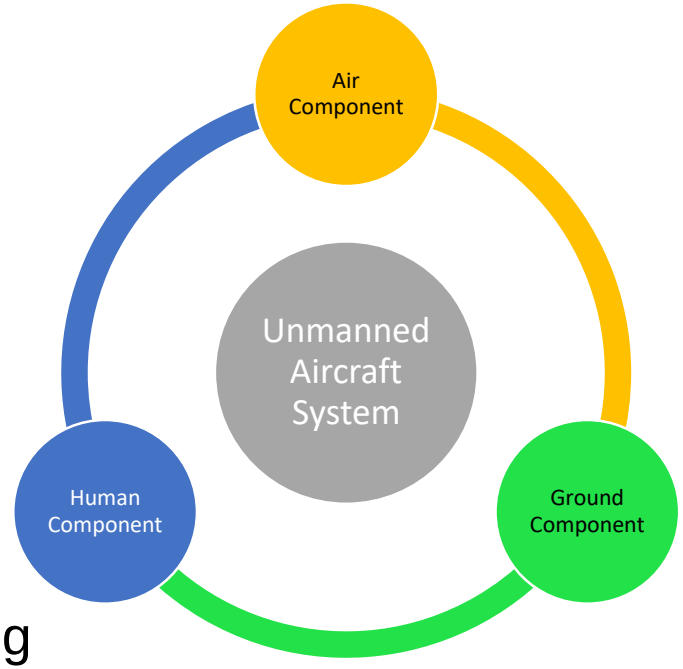
Small UAV Testing

- Launch and Recovery
  - Test entire system
  - Stability and control during transition
  - Vertical/horizontal error tolerance
  - Logical “weight-on-wheels”
  - One data point per sortie
  - System/Environmental Limitations

Will this soldier’s arm produce adequate forward velocity?

Small UAV Testing

- Human Factors
  - Humans are part of the System!
    - Air Vehicle Operators
    - Payload Operators
    - Maintainers
    - Consumers
  - Use by non-aviation personnel
    - Unaccustomed to aviation-style testing
    - Operational Limitations
      - Cold, wet, tired, hungry, angry Humans-in-the-Loop
    - “Best Practice” TTP development
    - Test with fielded support systems
      - Electrical generators
      - Radios and antennas
      - Sensor data receivers



Small UAV Testing

- Survivability
  - Conventional approach: “Will the human survive?”
  - Small UAV approach: “Will the human survive?”

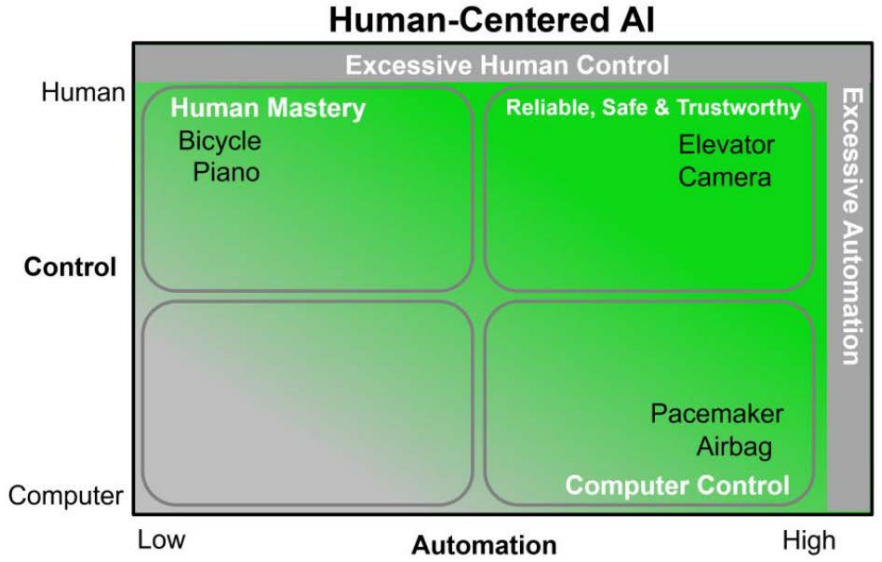
Small UAV Testing

- Survivability
  - The datalink is the weakest link
  - With COTS systems, we often field “as-is”
  - Evaluate in context of intended adversary environment
    - Most Likely Case: Detection & Geolocation
    - Most Dangerous Case: Exploitation & Weaponization
  - Identify and characterize the vulnerabilities
  - Develop mitigations and workarounds
    - Field-modified waveforms and encryption
    - Antenna directional masking
    - Antenna physical offset or retransmission
    - Reduced emissions (e.g. increasing autonomy)

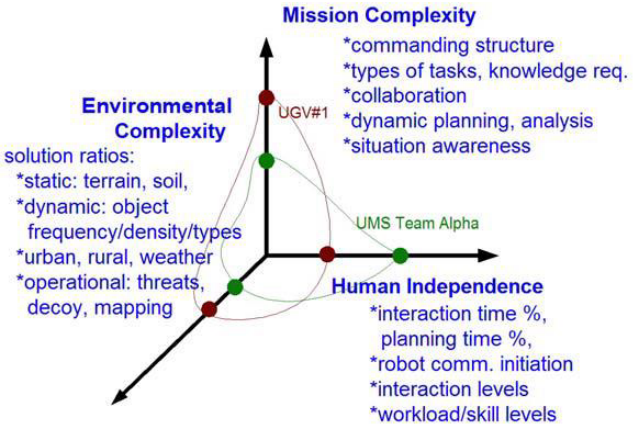
To emit is to be targeted.
Treat every emission as if your life depends on it.

Highly Autonomous Systems

- Definition of “Autonomous”
  - No single authoritative source for all use cases!



Taxonomy of Autonomy		
Autonomy Level	**Description**	**Colloquial Analogy**
1	Human gives commands, with no machine assistance	Teleoperation
2	Human gives commands, with several machine-aided options	Low-level decision support
3	Human gives commands, with few machine-aided options	Medium-level decision support
4	Human gives commands, with single machine-aided option	High-level decision support
5	Machine makes decisions, with human approval	Human-in-the-loop
6	Machine makes decisions, with human veto power	Human-on-the-loop
7	Machine makes decisions, and informs human	Human-near-the-loop
8	Machine makes decisions, and informs human upon request	Human-aware-of-the-loop
9	Machine makes decisions, and informs human if it decides to	Human-unaware-of-the-loop
10	Machine makes decisions, and does not inform human	Human-not-required



Highly Autonomous Systems

- Definition of “Autonomous”
  - Spectrum of Decision-Making

Automobile Navigation

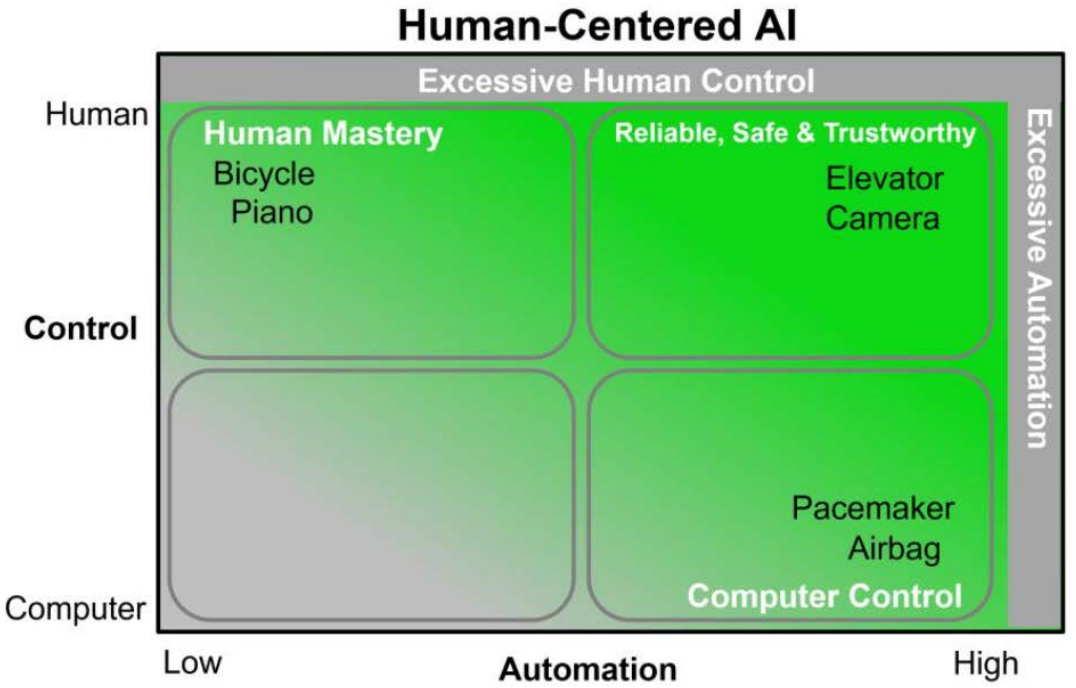
  - Spectrum of Action-Taking

Automobile Navigation

  - Who is giving commands? Who is taking them?
    - Human = “Steering Wheel Actuator”

Highly Autonomous Systems

- Philosophy of Testing
  - How much authority should the machine have?
  - How much authority should the human have?
  - Which tasks are best performed by which actor(s)?
  - System components:
    - Machine
    - Human



Highly Autonomous Systems

- Philosophy of Testing
  - Functional allocation approach

Autonomous VTOL Landing Allocation and Evaluation Criteria			
	Human	**Machine**	**Criterion**
Landing site selection	90%	10%	P_S of depicting potential landing zone = 0.8
Landing site survey	50%	50%	Surveys site size and slope +/- 10% error
Obstacle detection	50%	50%	P_D of obstacle > $1m^3$ = 0.9
Commit to landing spot	100%	0%	< 1m horizontal error in spot selection
Approach to landing spot	0%	100%	Maintains 300 +/- 25 fpm descent from 500' AGL to 10' AGL
Touchdown	0%	100%	Maintains 100 +/- 10 fpm descent from 10' AGL to surface Touchdown point +/- 1m from intended landing spot
Ground sensing	0%	100%	P_S of weight-on-wheels detection = 0.95
Abort landing	75%	25%	P_S of autonomous abort in fouled zone = 0.8 < 1 sec reaction time to operator-commanded abort

  - Where did the trial go right?
  - Where did the trial go wrong?

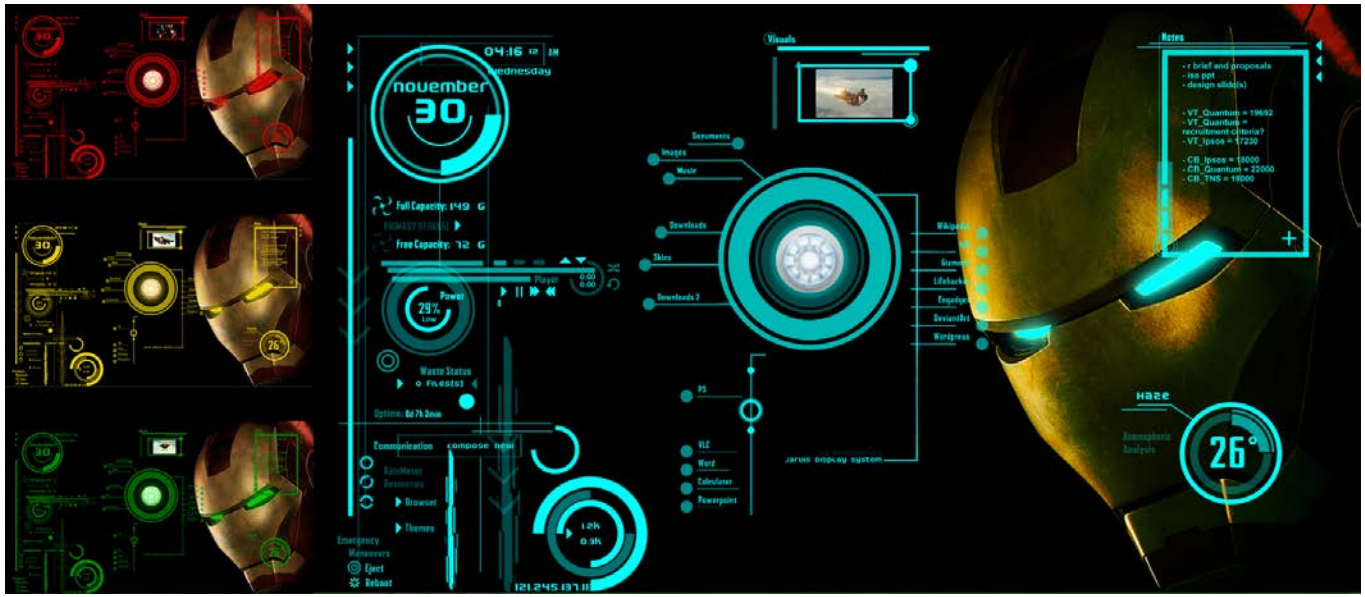
Highly Autonomous Systems

- Fundamental Test Approach
  - Decouple the challenges!
  - Test the *skeleton and muscles*
    - Air Vehicle
    - Launch/Recovery Equipment
    - Ground Control Station

  - Test the *brain and nervous system*
    - Flight controller
    - Autonomy engine
    - Sensor fusion engine
    - Decision-making algorithms

Highly Autonomous Systems

- Fundamental Test Approach
  - Platform Testing
    - Traditional techniques for performance, flying qualities, etc.
    - Increase pilot control in lieu of autonomous control
  - Autopilot Testing
    - Engineering Test Command (ETC) library to excite modes
    - “Snatchback” capability to regain human control



Highly Autonomous Systems

- Fundamental Test Approach
  - Autonomous Ground Testing
    - Systems Integration Laboratory (SIL) is imperative to match software with representative hardware
    - Testers simulate and stimulate the system under test with representative data
    - May be conducted in parallel with airframe testing
    - “Machine Speed” vs “Human Speed” testing
    - Entire span of conditions
      - Includes those impractical or unsafe for live flight
    - Predicted/Theoretical results vs Observed/Experimental results
      - What was expected? What happened?
    - Hygiene and Integrity of input data and internal libraries
      - Garbage In, Garbage Out.

Rigorous ground testing produces a “should-act” baseline for future flight test comparison.

Highly Autonomous Systems

- Fundamental Test Approach
  - Autonomous Flight Testing
    - *Complete Platform Test and Autonomy Ground Test First!*
    - SIL = Reduced Risk
    - Discovery of unanticipated inputs
    - Assume that “Snatchback” overrides will be used every flight
    - Train crews in every foreseeable emergency
    - Consider surrogate platforms
    - Start with simple scenarios with predicted outcomes
    - Slowly increase complexity
      - Virtual stimulators or cooperators
      - Live stimulators or cooperators
      - Ad hoc environmental changes
      - Training exercise “fog of war”

Use “Escalation of Force” with Operational Force introduction.

Highly Autonomous Systems

- Potential Problem Areas
  - Inadequate airframe testing
    - Autonomous systems cannot be tested from a smoking crater
  - Perception of autonomy as safety backup
    - System that performs poorly under human control not likely to perform much better under human-designed machine control
  - Premature insertion of high-level autonomy
    - IT industry thrives on “beta-version” releases
    - Minimal aviation appreciation by average SW developer

The Test Team is its own best defense against immature algorithms

Highly Autonomous Systems

- Swarms
  - Collection of multiple UAVs
  - Cooperative and Collaborative operations
  - “Multiplatorm sensors”
  - “One-to-Many” Human:UAV ratio
  - Homogenous vs Heterogeneous
  - Redundant and fault-tolerant
  - Sum is greater than parts

  - Examples
    - Expanded sensor field of view/regard
    - Multiple perception angles of target
    - Multiple sensor types
    - Daisy-chain LOS data links
    - Distributed logistics transportation
    - Saturate IADS
    - Mothership

“Quantity has a quality all its own.”

Highly Autonomous Systems

- Swarms
  - Adopt “system of systems” approach
  - Define every node’s function and assign metrics
  - Test subsystems in isolation (when able)
  - Aggregate platforms incrementally

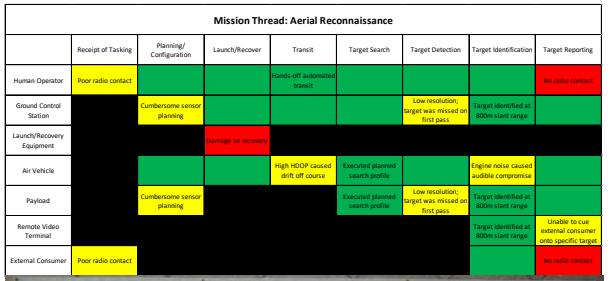
  - ~~Operator~~ Swarm Commander workload
    - Cognitive burden may be limiting factor in employment
  - Account for asset attrition/degradation

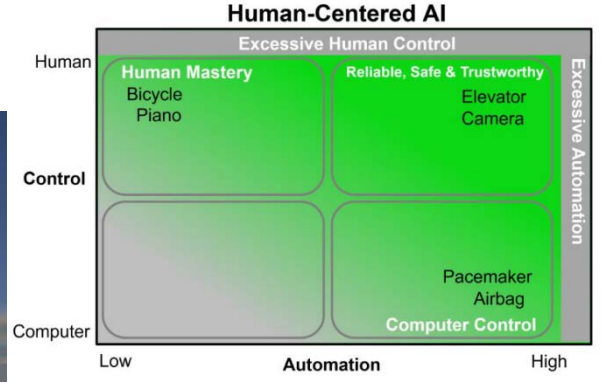
  - Does it perform the function at an acceptable level?

The strength of the Pack is the Wolf.
The strength of the Wolf is the Pack.

Summary

- Small UAV Testing
  - Consider “System of Systems”
  - Understand the purpose of test
  - UAS Safety protects humans
  - UAS Survivability protects humans
- Highly Autonomous Systems
  - Consider “System of Systems”
  - Task allocation
  - Phased approach to test
  - Strength in numbers





Questions / Discussion