AUTONOMY LEVELS FOR UNMANNED SYSTEMS (ALFUS)

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ALFUS Working Group

SAE AS4D Committee

ALFUS OBJECTIVES

Framework to facilitate characterizing and articulating autonomy for unmanned systems:

- Standard terms and definitions for requirements analysis and specification
- Metrics, processes, and tools for evaluation/measurement

ALFUS SCOPE

- Generic framework covering all UMSs.
- From remote control through full and intelligent autonomy.
- From single UMS subsystem level operational behavior through multi-level, joint missions.

HISTORY

- Stage I: Started in 2003 as Cross-Government Ad Hoc Workgroup. Published Terminology.
- Stage II: Collaboration with FCS. Published Framework.
- Stage III: January 2008, joined SAE as AS4-D Unmanned Systems Performance Measures Committee

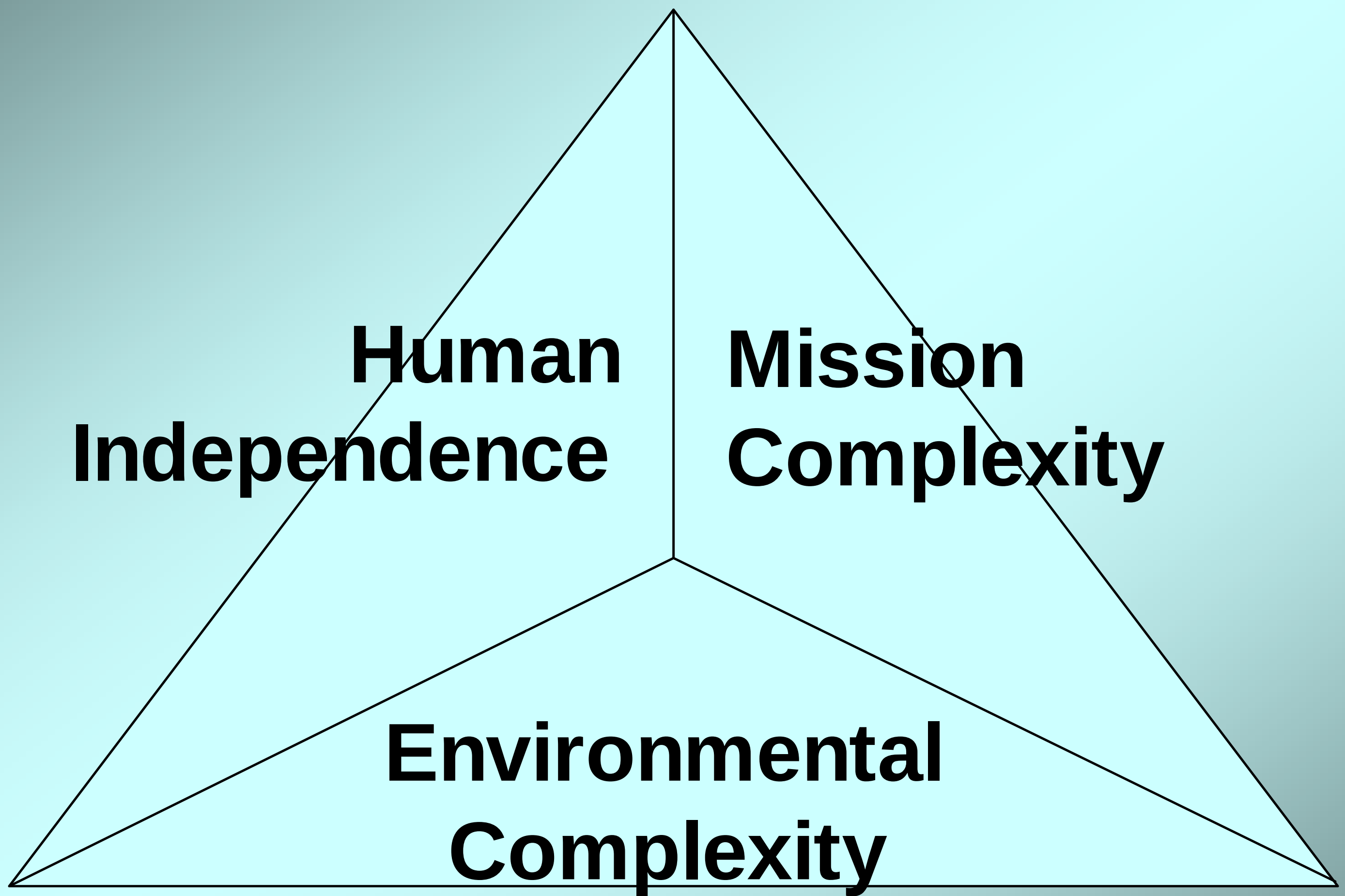
ALFUS CHARACTERISTICS

- Metrics based—measurable levels with smooth transitions
- Multiple layers of abstraction for autonomy requirements and capabilities
- Basis for a general performance metrics framework for unmanned systems

AUTONOMY
Focusing on Context

A UMS's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s) through designed HRI.

ALFUS FRAMEWORK



ALFUS METRICS

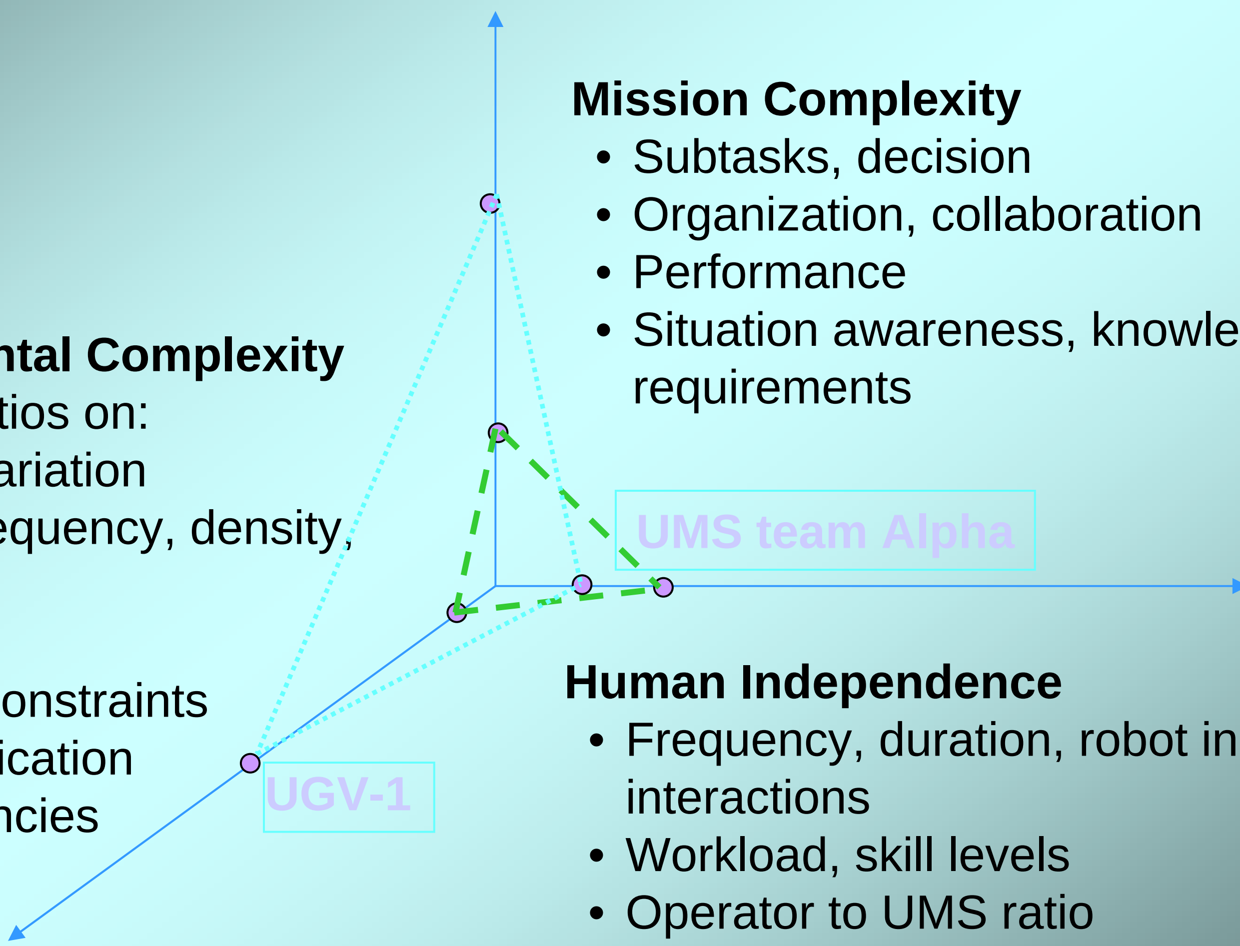
Mission Complexity

- Subtasks, decision
- Organization, collaboration
- Performance
- Situation awareness, knowledge requirements

Environmental Complexity

Solution ratios on:

- Terrain variation
- Object frequency, density, intent
- Climate
- Mobility constraints
- Communication dependencies



Human Independence

- Frequency, duration, robot initiated interactions
- Workload, skill levels
- Operator to UMS ratio

LAYERS OF DETAIL

taskstructure metricscore

subtasking metricscore

MC tactical behaviormetric groupscore

Metric Decomposition

MC metric score

CAC

HI metric score

EC metric score

- Metrics Groups

- Root Autonomous Capability Autonomy

Contextual Autonomous Capability:

- Mission/Task/UMS Autonomy

- Mission Complexity

- Environmental Complexity

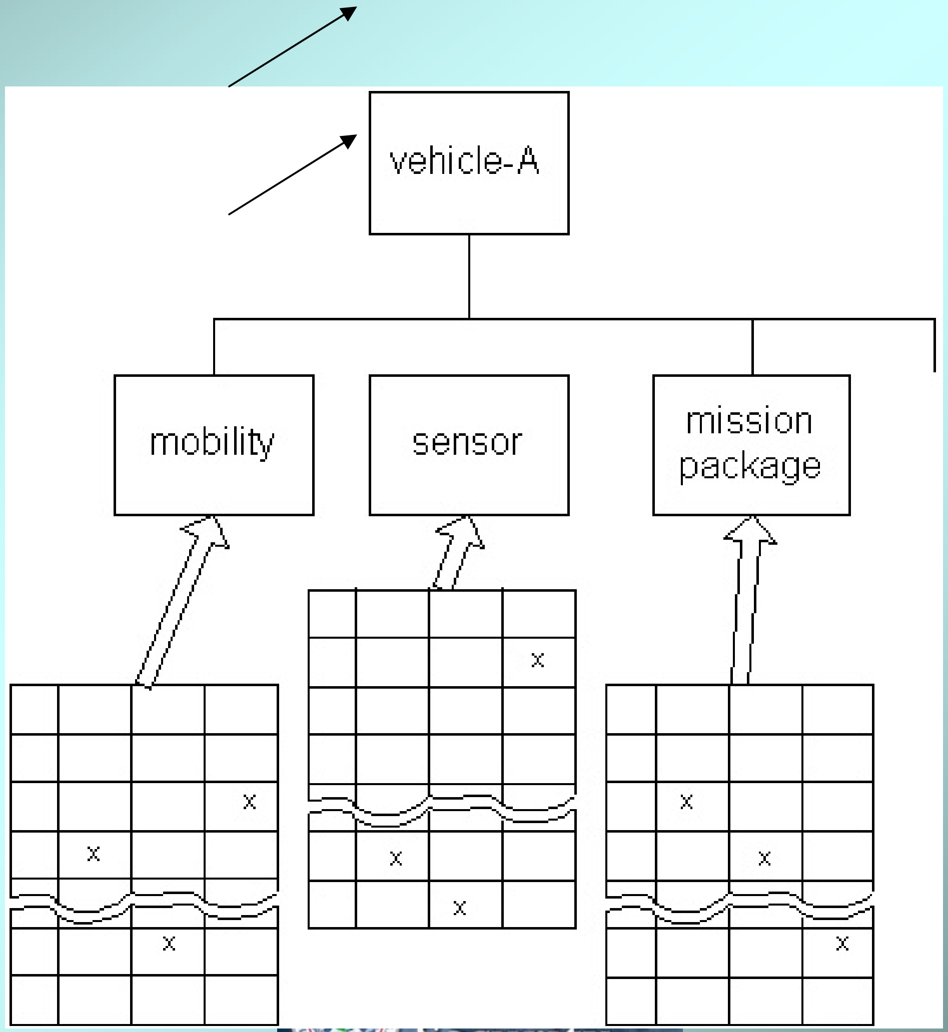
CONTEXTUAL AUTONOMY
Evaluation Form

autonomy levels

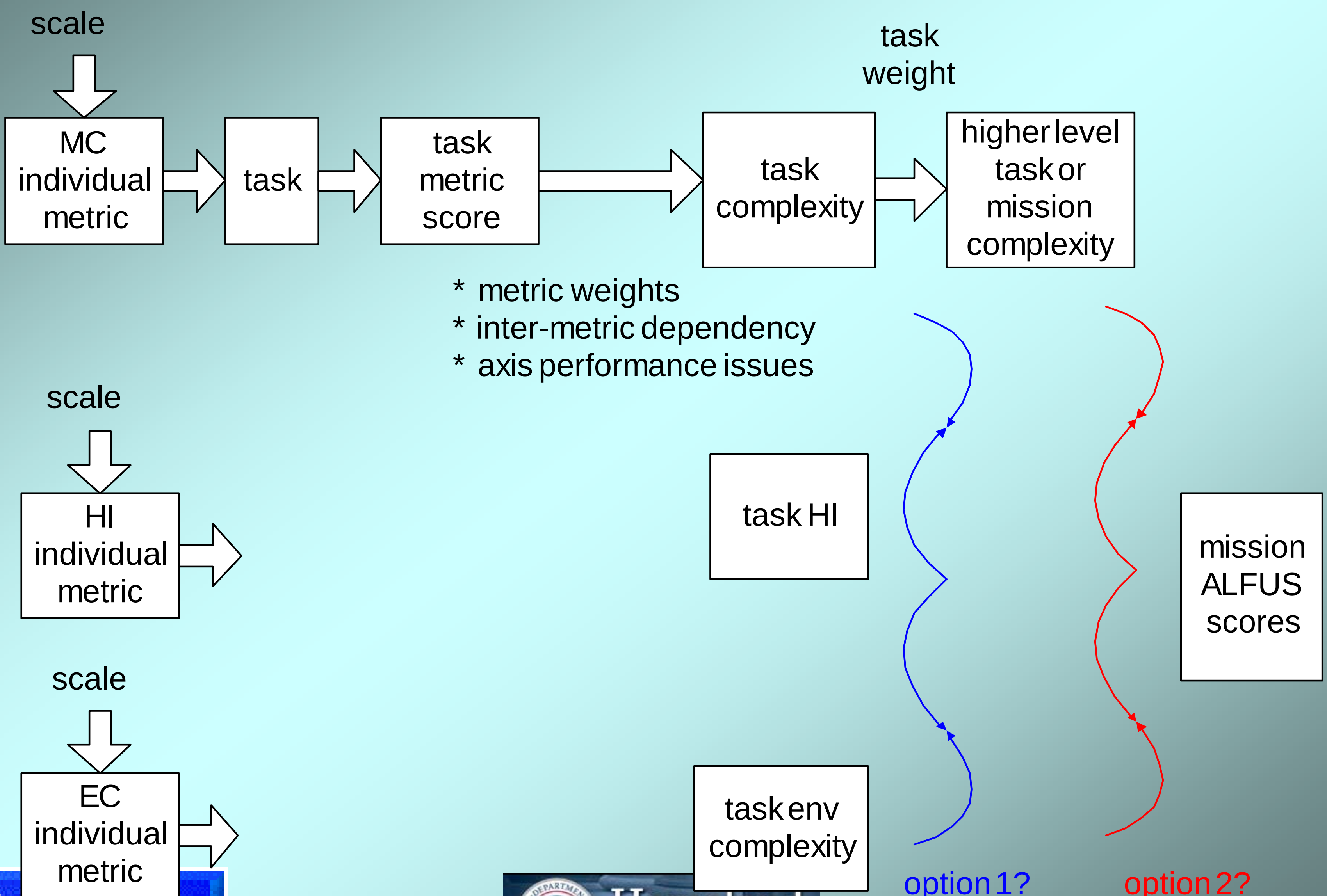
	MC	ED	HRI
10			
9			
8			
2			
1			

MC: mission complexyty,
ED: environmental difficulty
HRI: human-robot interaction

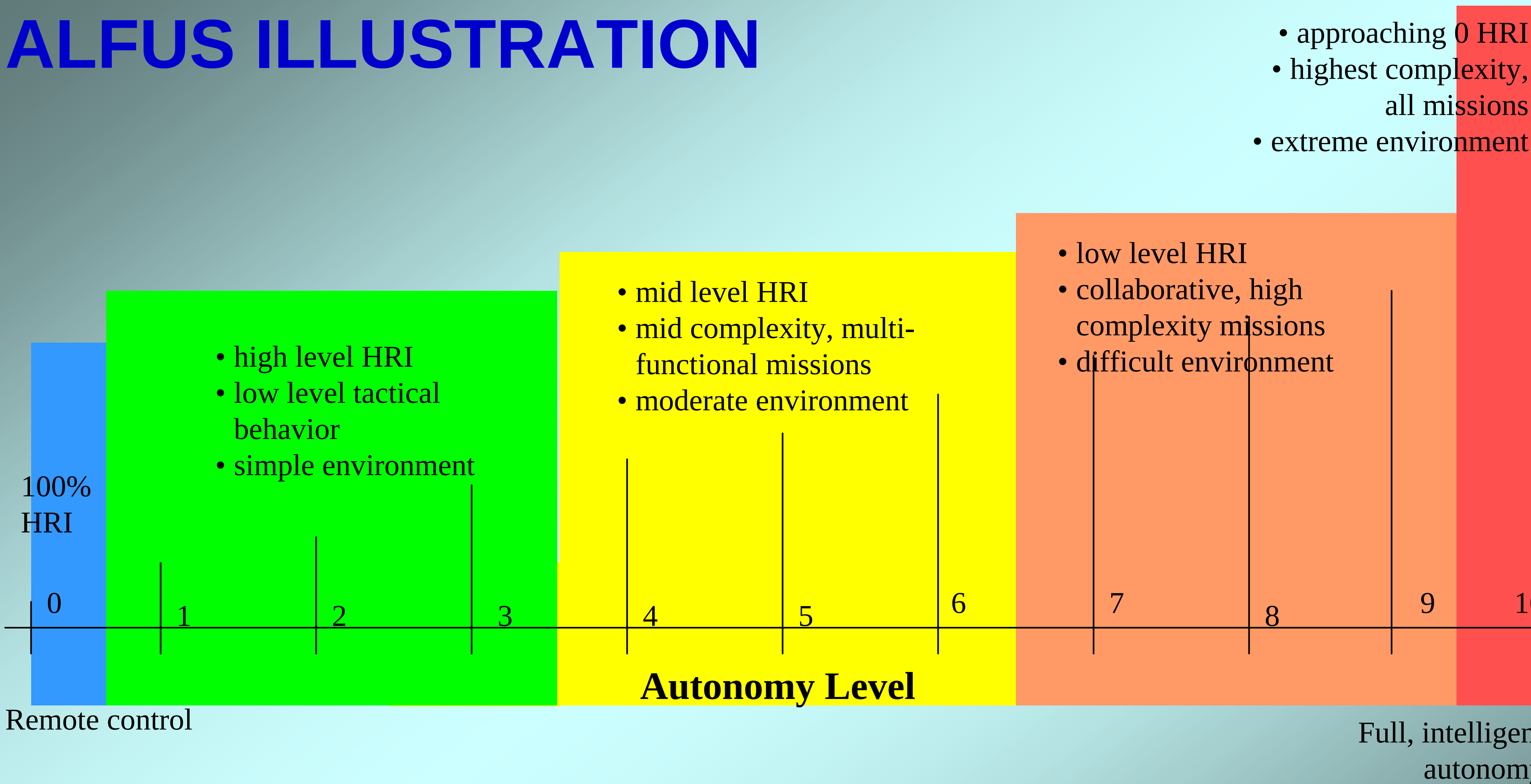
ALFUS FRAMEWORK
Illustrative Application



ALFUS EVALUATION PROCESS



ALFUS ILLUSTRATION

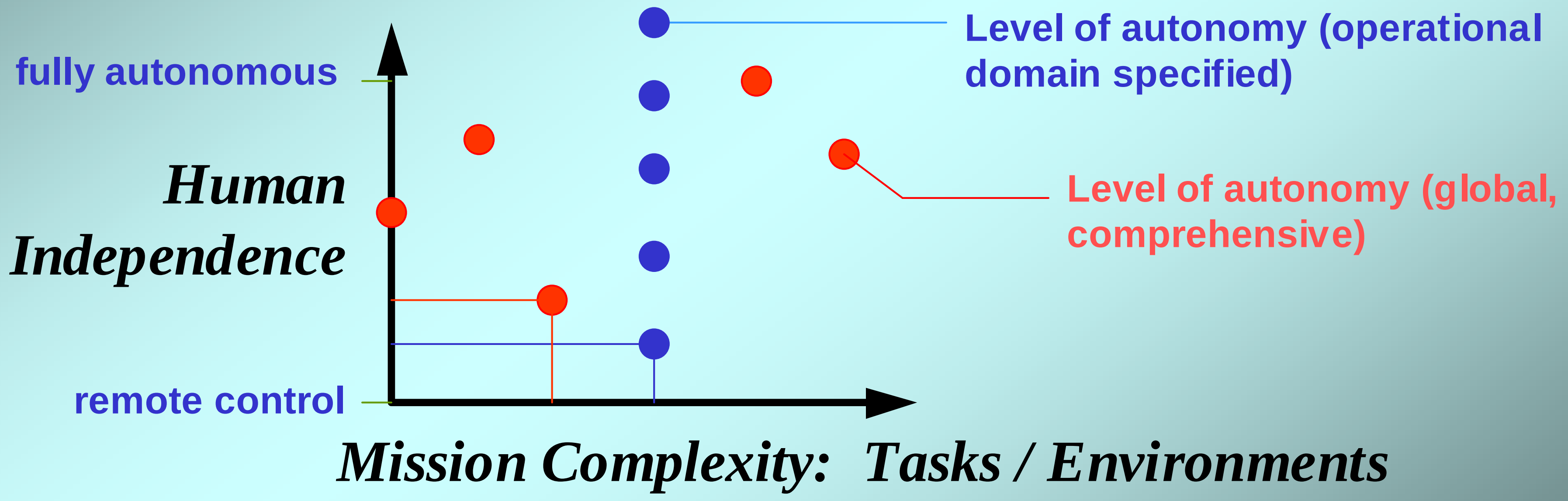


Single actuator → Single function → Single UMS → UMS team → SOS

Single actuator/ subfunction → Single function → Single UMS → team

ALFUS MODEL

Simplified by Combined Mission and Environment Axes



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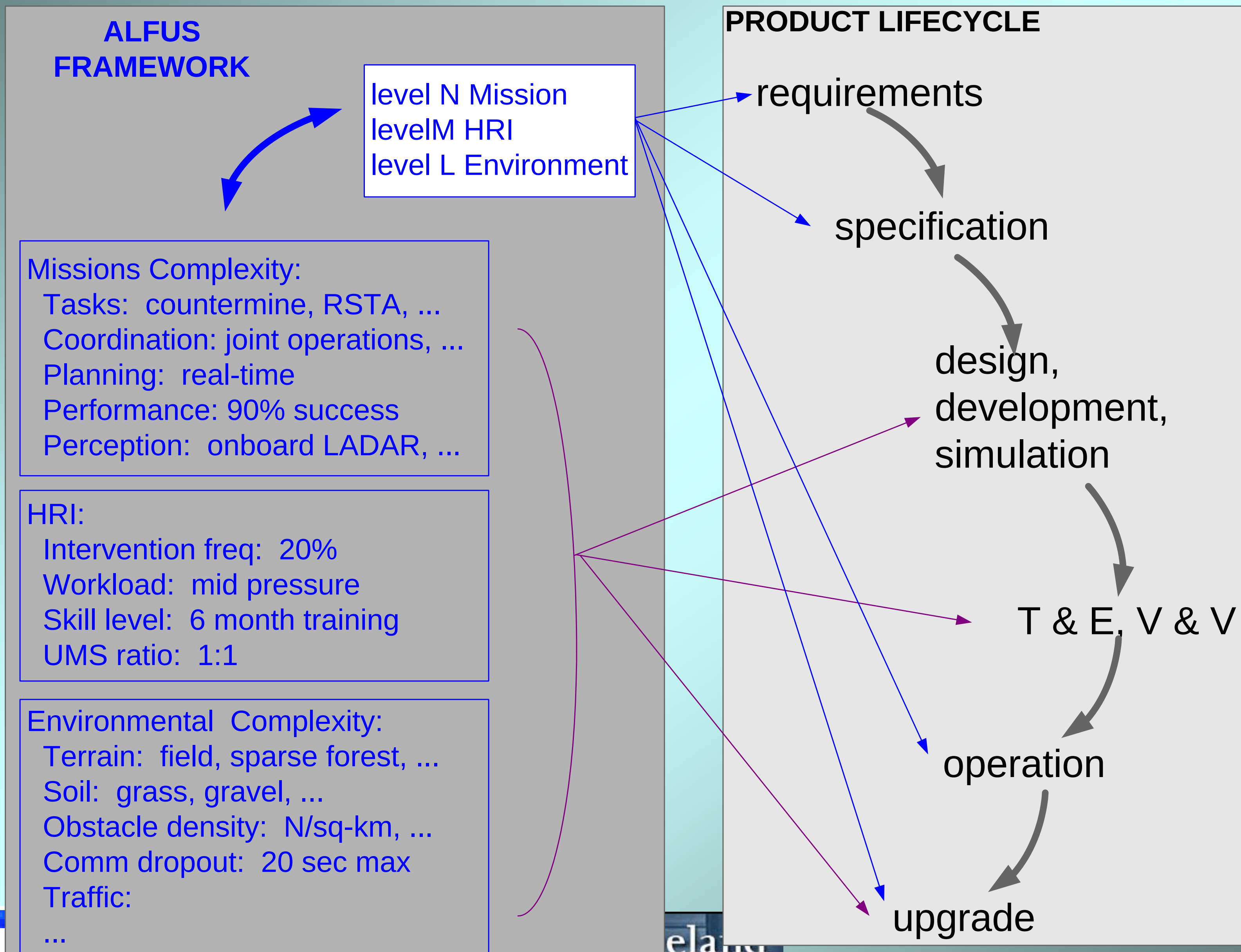
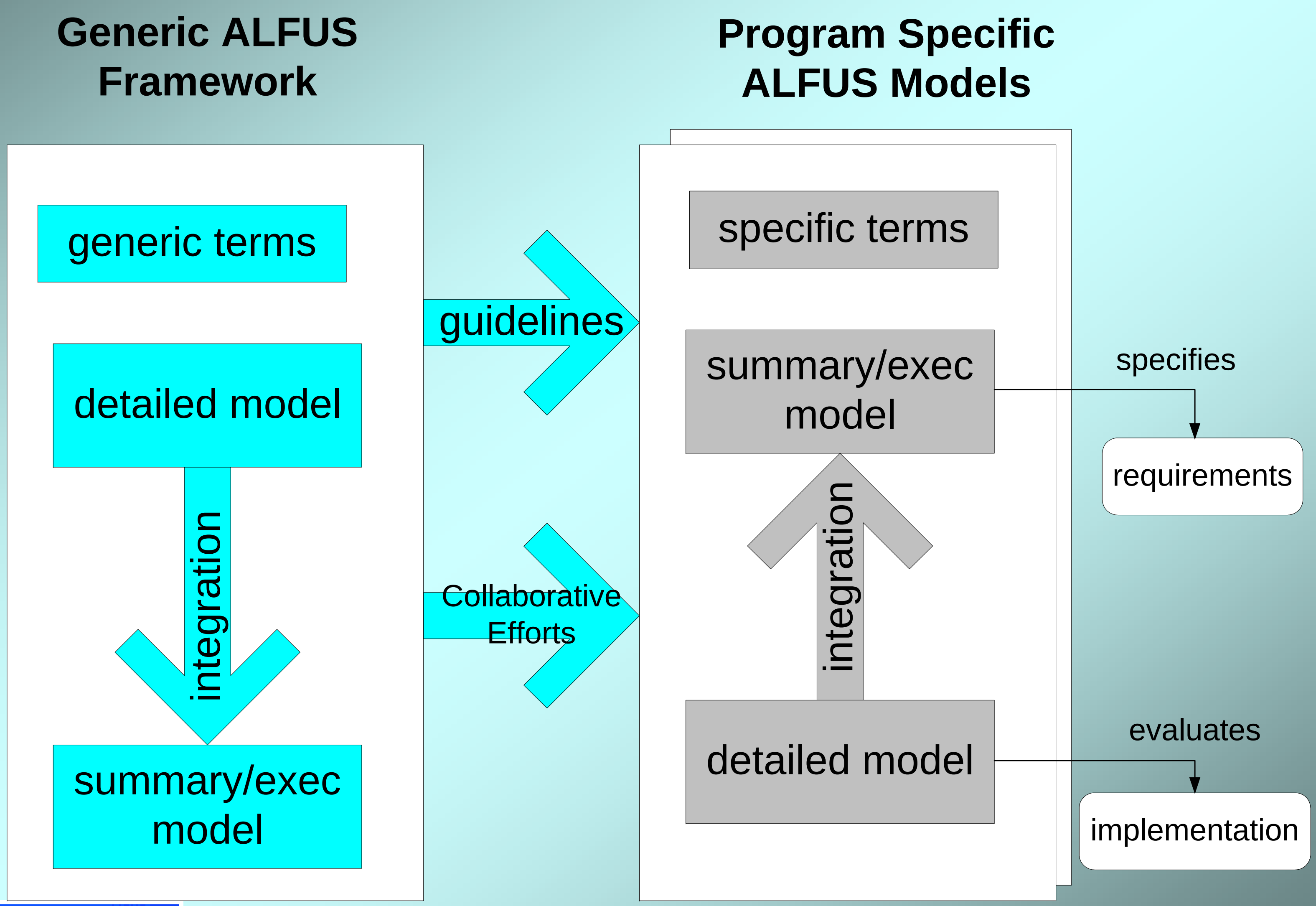
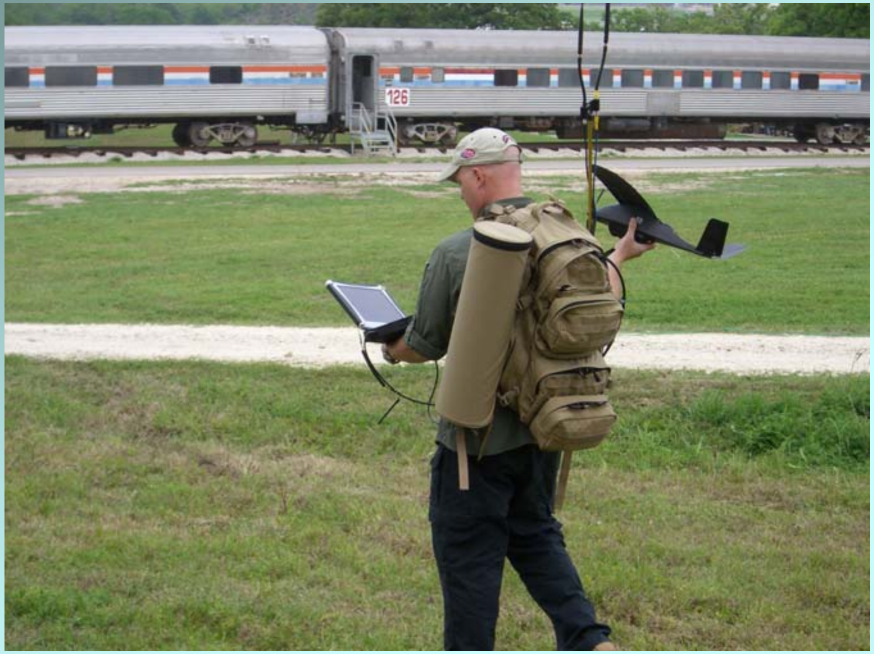
ALFUS FRAMEWORK APPLICATION



ALFUS FRAMEWORK



ALFUS GENERALIZATION
Performance Test Methods



SUMMARY

Framework to facilitate characterizing/ articulating autonomy levels for unmanned systems:

- Generic framework covering all UMSs.
- From remote control through full autonomy.
- From single UMS to team to joint missions.

http://www.nist.gov/mel/isd/ks/autonomy_levels.cfm

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BACKUPS

SUMMARY MODEL FORMAT (1)

Level and Descriptor	Metrics and Definition	Capability
10 – Full, intelligent autonomy	*Collaborative in team of teams, real-time planning to complete all required missions with highest complexity; understands, adapts to, and maximizes benefit/value/efficiency while minimizes costs/risks on the broadest scope environmental and operational changes; approaching total independence on information and from operator input.*	Any mission assigned to the team of teams in its native environment
	HRI Metrics: Requiring approaching zero human interaction after assigning mission.	
	Mission Complexity Metrics: • All required missions for SoS, highest level of subtasking and collaboration throughout organization. • Full, self, efficient, real-time planning and execution, highest precision and success rate, maximizes/minimizes on values/cost, benefit/risk. • Self-sufficient SA and KB, highest fusion/perception levels.	
	Environmental Difficulty Metrics: • Generate and assimilate highest fidelity map for mission, infer highest res info from low res • Adaptable to extreme terrain and climate variations and obstacle density and frequency. • Independence to comm. link with operator.	

PARTICIPATION (partial)

DOD – AATD*, AFRL, AMRDEC*, ARL*, MANCEN*, CERDEC*, DARPA, NAVAIR, NSWC, OSD/JPO, TARDEC*, TRADOC*, …

DOC – NIST

DOE – HQ, INEEL

DOT – FHWA

Industry

Collaborations with AIAA, JAUS WG, NASA, PerMIS, …

***U.S. Army**

NIST

Homeland Security

COTRIBUTORS (partial)

The following, in alphabetical order, contributed to the ALFUS Framework effort: **Air Force**: Bruce Clough, Robert Smith, Jeff Wit. **Army (inc. AATD, AMRDEC, ARL, CERDEC, MENCEN, TARDEC, TSM FCS, UAMBL)**: Curt Adams, Keith Arthur, Robert Barnhill, Bruce Brendle, Marsha Cagle-West, Jeff Cerny, Sanjiv Dungrani, Mike Dzugan, Woody English, Bill Fedak, Ray Higgins, Susan Hill, Julie Hirtz, Kelley Hodge, Jeffrey Jaczkowski, Robert Kania, David Knichel, Brian Maijala, Peter Melick, Brian Novak, Kerry Pavek, Richard Pena, Jason Pusey, John Rovegno, Kent Schvaneveldt, Charles Shoemaker, Stephen Swan, David Thomas, Terrance Tierney, Robert Wade. **DARPA**: LTC Gerrie Gage, Doug Gage, Dennis Overstreet. **DOE**: David Bruemmer, Tom Weber. **DOT FHWA**: Robert Ferlis, Peter Huang. **Industry (inc. FCS)**: Thomas Adams, Thomas Altshuler, John Bergman, Charles Bishop, Dale Fleck, William Klarquist, Mark Peot, Dan Rodgers, Chiraq Tasker. **IDA**: Julianna Connelly, David Sparrow. **NASA**: Jeremy Hart, Ryan Proud. **Navy**: Darryl Brayman, Eric Hansen, Caesar Mamplata, Marc Steinburg. **NIST**: James Albus, Brian Antonishek, Tony Barbera, Maris Juberts, Elena Messina, Jean Scholtz, Harry Scott, Albert Wavering. **OSD**: Richard Abraham, Keith Anderson, Jeffrey Kotora. **apologize for the omitted contributors.**

Project Funding: DHS and NIST

Existent Work--NASA SMART

Each Level of Autonomy Scale is broken into 8 levels. The levels for the Decide functions are shown.

More Autonomy

8	The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human.	**4**	Both human and computer perform ranking tasks, the results from the computer are considered prime.
7	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the	**3**	Both human and computer perform ranking tasks, the results from the human are considered prime.
6	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	**2**	The human performs all ranking tasks, but the computer can be used as a tool for assistance.
5	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	**1**	The computer does not assist in or perform ranking tasks. Human must do it all.

Less Autonomy

EXISTENT WORK
Essential Foundations

- OODA -- Observe, Orient, Decide, Act.

- 4D/RCS Reference Architecture
  - Generic Node consistent with OODA
  - System Hierarchy harmonizes many, many OODA nodes.
  - Hierarchical Task Decomposition organizes missions of different complexity.

EXISTENT WORK

Level	Level Descriptor	Observe Perception/Situational Awareness	Orient Analysis/Coordination	Decide Decision Making	Act Capability
10	Fully Autonomous	Cognizant of all within Battlespace	Coordinates as necessary	Capable of total independence	Requires little guidance to do job
9	Battlespace Swarm Cognizance	Battlespace inference - Intent of self and others (allies and foes). Complex/Intense environment - on-board tracking	Strategic group goals assigned Enemy strategy inferred	Distributed tactical group planning Individual determination of tactical goal Individual task planning/execution Choose tactical targets	Group accomplishment of strategic goal with no supervisory assistance
8	Battlespace Cognizance	Proximity inference - Intent of self and others (allies and foes) Reduced dependance upon off-board data	Strategic group goals assigned Enemy tactics inferred ATR	Coordinated tactical group planning Individual task planning/execution Choose targets of opportunity	Group accomplishment of strategic goal with minimal supervisory assistance (example: go SCUD hunting)
7	Battlespace Knowledge	Short track awareness - History and predictive battlesp data in limited range, timeframe, and numbers Limited inference supplemented by off-board data	Tactical group goals assigned Enemy trajectory estimated	Individual task planning/execution to meet goals	Group accomplishment of tactical goal with minimal supervisory assistance
6	Real Time Multi-Vehicle Cooperation	Ranged awareness - on-board sensing for long range, supplemented by off-board data	Tactical group goals assigned Enemy location sensed/estimated	Coordinated trajectory planning and execution to meet goals - group optimization	Group accomplishment of tactical goal with minimal supervisory assistance Possible close air space separation (1-100 yds)
5	Real Time Multi-Vehicle Coordination	Sensed awareness - Local sensors to detect others, Fused with off-board data	Tactical group plan assigned RT Health Diagnosis; Ability to compensate for most failures and flight conditions; Ability to predict onset of failures (e.g. Prognostic Health Mgmt) Group diagnosis and resource management	On-board trajectory replanning - optimizes for current and predictive conditions Collision avoidance	Group accomplishment of tactical plan as externally assigned Air collision avoidance Possible close air space separation (1-100 yds) for AAR, formation in non-threat conditions
4	Fault/Event Adaptive Vehicle	Deliberate awareness - allies communicate data	Tactical plan assigned Assigned Rules of Engagement RT Health Diagnosis; Ability to compensate for most failures and flight conditions - inner loop changes reflected in outer loop performance	On-board trajectory replanning - event driven Self resource management Deconfliction	Self accomplishment of tactical plan as externally assigned Medium vehicle airspace separation (100's of yds)
3	Robust Response to Real Time Faults/Events	Health/status history & models	Tactical plan assigned RT Health Diag (What is the extent of the problems?) Ability to compensate for most control failures and flight conditions (i.e. adaptive inner-loop control)	Evaluate status vs required mission capabilities Abort/RTB if insufficient	Self accomplishment of tactical plan as externally assigned
2	Changeable Mission	Health/status sensors	RT Health diagnosis (Do I have problems?) Off-board replan (as required)	Execute preprogrammed or uploaded plans in response to mission and health conditions	Self accomplishment of tactical plan as externally assigned
1	Execute Preplanned Mission	Preloaded mission data Flight Control and Navigation Sensing	Pre/Post Flight BIT Report status	Preprogrammed mission and abort plans	Wide airspace separation requirements (miles)
0	Remotely Piloted Vehicle	Flight Control (attitude, rates) sensing Nose camera	Telemetered data Remote pilot commands	N/A	Control by remote pilot

Table 4: Final ACL Chart

EXISTENT WORK

"Sheridan" Model

1) Computer offers no assistance, human must do it all.
2) Computer offers a complete set of action alternatives, and
3) narrows the selection down to a few, or
4) suggests one, and
5) executes that suggestion if the human approves, or
6) allows the human a restricted time to veto before automatic execution, or
7) executes automatically, then necessarily informs the human, or
8) informs him after execution only if he asks, or
9) informs him after execution if it, the computer, decides to.
10) Computer decides everything and acts autonomously, ignoring the human.

EXISTENT WORK
Army Science Board Study

0. Manual remote control, like a remote controlled toy
1. Simple automation
2. Automated tasks and functions, like a Hunter
3. Scripted mission, like an Shadow or Predator UAV
4. Semi-automated missions with simple decision making, like an Cruise Missile
5. Complex missions-specific reasoning
6. Dynamically mission adaptable
7. Synergistic multi-mission reasoning
8. Human-like autonomy in a mixed team
9. Autonomous teams with unmanned leader or mission manager
10. Autonomous conglomerate.

Existent Work

Level	Level Description	Observation Perception/ Situation Awareness	Decision Making	Capability	Example
1	Remote Control	Remote camera images viewed by operator	None	Remote operation in relatively simple stationary environments	Basic teleoperation
2	Remote Control w/vehicle State Knowledge	Local pose, dash-board sensors, and depth image display for operator	Basic health and vehicle state reporting	Remote operation in relatively complex stationary environments	Teleoperate with operator knowledge of geometry of environment
3	Pre-Planned mission or retro-traverse	INS/GPS waypoints, collision avoidance	ANS commanded steering based on planned path	Basic path following with operator help	Pre-planned path, retro-traverse, or operator waypoint selection
4	On-board processing of sensory images	Perception of simple surfaces and shapes	Negotiation of simple environment	Robust leader follower with operator help	Follow foot soldiers on road march or easy cross-country
5	Simple obstacle detection and avoidance	Local perception and map database	Real-time path planning based on hazard estimation	Basic cross country semi-autonomous navigation	Cross country with frequent operator intervention
6	Complex obstacle detection and avoidance, terrain analysis	Perception and world model representation of local environment	Planning and negotiation of complex terrain and objects	Cross country with obstacle negotiation with some operator help	Cross country in complex terrain with limited intervention
7	Moving object detection and tracking, on-road and off-road autonomous driving	Local Sensor fusion with a priori maps of road network, representation of moving objects	Robust Planning and Negotiation of Complex Terrain, Environmental Conditions, hazards and objects	Cross country with obstacle avoidance with little operator help	Cross country in complex terrain with full mobility speed with limited intervention
8	Cooperative operations, convoy, intersections, on-coming traffic	Real-time fusion of data from external sources, broad knowledge of rules of the road	Advanced decisions based on shared data from other similar vehicles	Rapid effective execution of on-road driving tasks with minimal operator input	On-road operations under normal road conditions with little supervision
9	Collaborative operation, traffic signs and signals, near human levels of driving skill	Perception in bad weather and difficult environmental conditions	Collaborative reasoning for cooperative tactical behaviors	Accomplish complex collaborative missions with some operator oversight	Effective combat mission accomplishment with little supervision
10	Full autonomy with human levels of performance or better	Data fusion from all participating battlefield assets	Total independence to plan and implement to meet defined objectives	Accomplish complex collaborative missions with no operator intervention	Fully autonomous combat missions accomplished with results equal to or better than with human soldiers

- **As Autonomy increases capabilities include or replace items from lower levels**
- **The same Behavior operating in different Terrain and/or Environmental conditions may result in different level of autonomy**

ALFUS GENERIC FRAMEWORK

Detailed Model

Characterization of Human Independence

- Intervention frequency/duration
- Robot initiation percentage
- Operator workload
- Operator to UMS ratio
- Operator Skill

ALFUS GENERIC FRAMEWORK

Detailed Model

Characterization of Environmental Complexity

- static: terrain, soil, water,
- dynamic: frequency/density/types of objects
- electronic/electromagnetic
- urban: traffic, road, barriers, controlling devices
- rural: vegetation, biologics,
- weather: climate, lighting, temperature,
- operational: threats, decoy, mapping, mobility,

Autonomy Level Algorithms mission complexity axis

1. “Serial”: Add values for all metrics and scale them from 0 to 10.
   - Advantage: simple and mechanic,
   - Drawback: final number may be misleading or vague. For example, a level 7 may be a result of very high subordinate level numbers but very poor latency and that may not be what the user wanted.

2. “Parallel”: line up all the metric values and pick the lowest.
   - Advantage: assurance
   - Drawback: over constraining, high cost for ums development.

3. “Hybrid”: Categorize mission metrics into: O, O, D, and A. Use serial within each category but parallel for the 4 categories?

ALFUS FRAMEWORK
Clarification

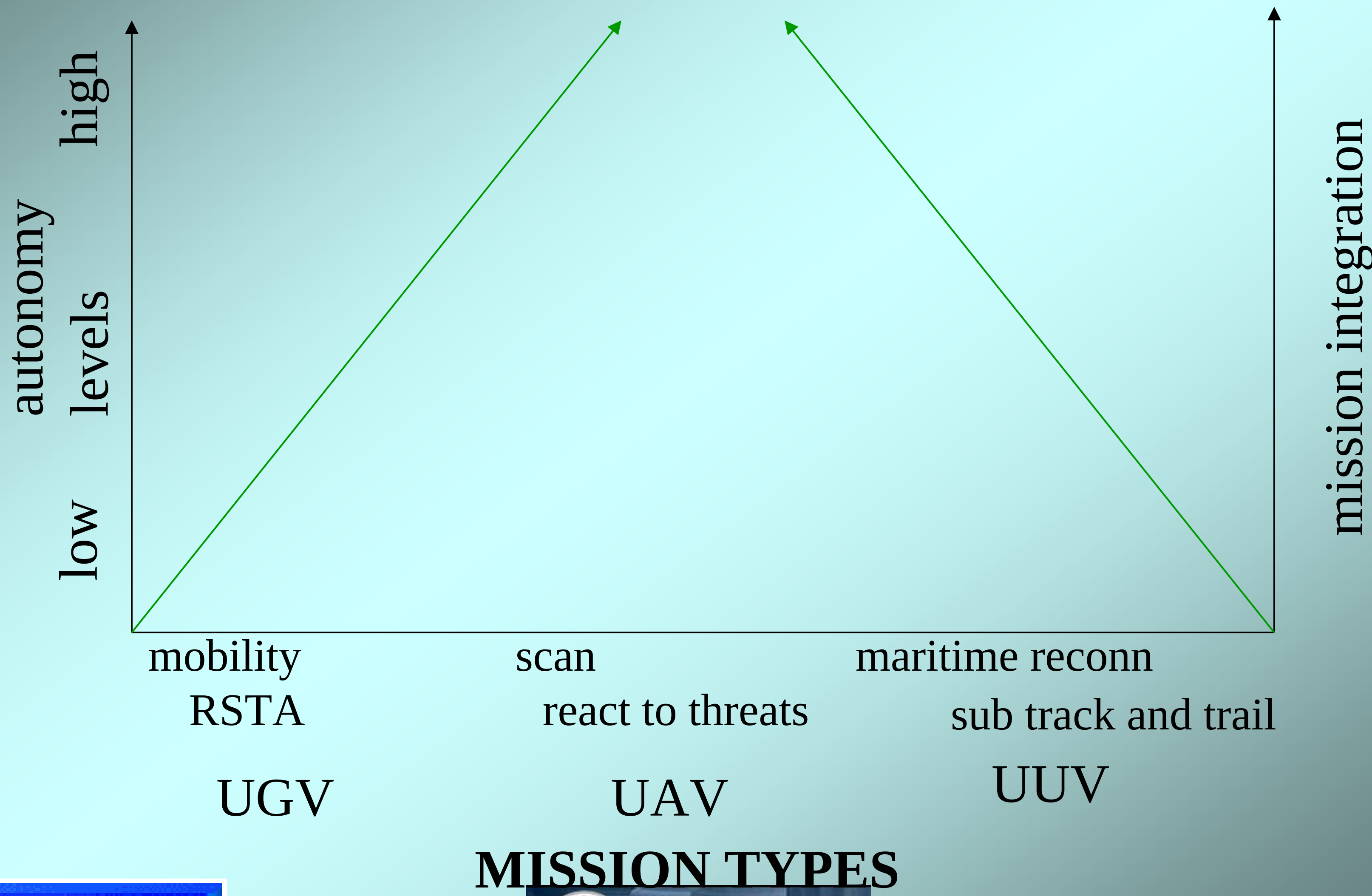
Autonomy vs. Automation

- washing machine vs. scouting mission
- human-less operation vs. human-like performance

Some possible uses of the framework

- Classify environments, HRI systems, or missions
- Missions can be certified with the other two axes, e.g., perform mission A in level N environment, mission B is designed to operate with level M HRI, etc.
- Detailed metrics could be used as general performance metrics for intelligent, unmanned systems.

JOINT MISSIONS



Workshop Accomplishments

- Inaugural Workshop (July 18, 2003, NIST)
  Established Working Group Objectives
- Second (September 11, 2003, BWI)
  Identified Terms and Started Definitions
- Third (November 22, 2003, SRS Tech., Arlington, VA)
  Identified Metrics, Terminology Published
- Fourth (February 25-26, 2004, Titan Sys., Huntsville, AL)
  Identified Summary Model Representation

Workshop Accomplishments

- Fifth (May 3-4, 2004, Atlanta Airport, GA)

  Metrics and Measures Presented. Began Interaction with FCS
- Sixth (July 28-29, 2004, FCS LSI, Huntsville, GA)

  Tool Conceptualized. Exit Strategy Planned.
- Seventh (October 19-20, 2004, AFRL, Dayton, Ohio)

  Tool Updated. Began Summary Model.
- Eighth (February 8 - 9, 2005, NIST, Gaithersburg, Maryland)

  Continued Developing Models. NIST 4D/RCS Task Analysis Method Presented. DOT ITS Briefed.

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Workshop Accomplishments

- Ninth (May 4-5, 2005, TARDEC, Warren, Michigan)

  Focused on Metric Scale Development. TARDEC Programs Presented. ASBS and UACO Programs Briefed.

- Tenth (July 20-21, U.S.Army Futures Center Forward, Arlington, Virginia)

  Further Development on Metric Scales. Additional Representation Presented.