Metrics, Schmetrics! How The Heck Do You Determine A UAV's Autonomy Anyway?

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ABSTRACT

The recently released DoD Unmanned Aerial Vehicles Roadmap [*9*] discusses advancements in UAV autonomy in terms of autonomous control levels (ACL). The ACL concept was pioneered by researchers in the Air Force Research Laboratory's Air Vehicles Directorate who are charged with developing autonomous air vehicles. In the process of developing intelligent autonomous agents for UAV control systems we were constantly challenged to "*tell us how autonomous a UAV is, and how do you think it can be measured…*" Usually we hand-waved away the argument and hoped the questioner will go away since this is a very subjective, and complicated, subject, but within the last year we've been directed to develop national intelligent autonomous UAV control metrics - an IQ test for the flyborgs, if you will. The ACL chart is the result. We've done this via intense discussions with other government labs and industry, and this paper covers the agreed metrics (an extension of the OODA - observe, orient, decide, and act - loop) as well as the precursors, "dead-ends", and out-and-out flops investigated to get there.

Keywords: autonomy metrics, machine intelligence metrics, UAV, autonomous control

1. Background

At top levels of the US Department of Defense an effort has been initiated to coordinate researchers across the Services and industry in meeting national goals in fixed-wing vehicle development. The Fixed-Wing Vehicle Initiative (FWV) has broad goals across numerous vehicle technologies. One of those areas is mission management of UAVs. Our broad goal is to develop the technology allowing UAVs to replace human piloted aircraft for any conceivable mission. This implies that we have to give UAVs some level of autonomy to accomplish the missions. One of the cornerstones of the FWV process is the establishment of metrics so one know that a goal is reached, but what metrics were available for measuring UAV autonomy? Our research, in conjunction with industry, determined that there was not any sort of metric as we desired. Thus we set out to define our own [Note 1].

But what characteristics should these metrics have? We decided that they needed to be:

- Easily visualized such that upper management could grasp the concepts in a couple of briefing slides.
- Broad enough to measure past, present and future autonomous system development.
- Have enough resolution to easily track impact of technological program investments.

So, they had to be simple, apply to a broad range of systems, and yet exhibit good resolution. Obviously a simple task, but first let's look at what it means to be autonomous.

2. Quick Difference Between Autonomous and Automatic (our definition)

Many people don't realize that there is a significant difference between the words autonomous and automatic. Many news and trade articles use these words interchangeably. Automatic means that a system will do exactly as programmed, it has no choice. Autonomous means that a system has a choice to make free of outside influence, i.e., an autonomous system has free will. For instance, let's compare functions of an automatic system (autopilot) and an autonomous guidance system:

- Autopilot: Stay on course chosen.
- Autonomous Guidance: Decide which course to take, then stay on it.

Example: a cruise missile is not autonomous, but automatic since all choices have been made prior to launch.

3. We Need To Measure Autonomy, Not Intelligence

For some reason people tend to equate autonomy to intelligence. Looking through the proceedings of the last NIST Intelligent Systems Workshop there are several papers which do this, and in fact, the entire conference sets the tone that "intelligence is autonomy" [*3*]. They are not the same. Many stupid things are quite autonomous (bacteria) and many very smart things are not (my 3 year old daughter seemingly most of the time). Intelligence (one of a myriad of definitions) is the capability of discovering knowledge and using it to do something. Autonomy is:

- the ability to generate one's own purposes without any instruction from outside (L. Fogel)
- having free will (B. Clough)

What we want to know is how well a UAV will do a task, or better yet, develop tasks to reach goals, when we're not around to do it for the UAV. We really don't care how intelligent it is, just that it does the job assigned. Therefore, intelligence measures tell us little. So, although we could talk about the Turing Test [*1*] and other intelligence metrics, that is not what we wanted.

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4. Well, It Should Be Easy To Find Metrics, One Has The Web And Other Info Sources, Right?

Well, one would think so, but after an exhaustive one-month search involving the author, Air Force Research Laboratory Library Staff, and several other search organizations we found two. Two. Now if the goal was "find machine intelligence metrics" we would have been inundated with piles of paper. In addition to the aforementioned workshop, we would be looking through hundreds of publications and papers. Maybe it was a good thing we were looking for autonomy metrics!

We had thought that maybe, just maybe, the folks working distributed autonomous robotic systems had looked at this problem, but our questions to experts in that field revealed that they are just starting to ask those questions themselves [*4*]. The problem the researchers have in this area is that the metrics they are coming up with are task specific - they don't have general metrics quantitatively measuring higher-level characteristics of autonomous robot control architectures.

So what were the two that we found? Los Alamos National Laboratory's "Mobility, Acquisition, and Protection" space [*6*], and Draper Laboratory's "Three Dimensional Intelligence Space"[*7*]. The following is a short discussion of each [*Note 5*].

1. Los Alamos National Lab: Mobility, Acquisition, and Protection (MAP)

MAP comes from the lab of Mark Tilden, who develops simple robots based on analog circuits [*10*]. He needed a way to quantify the autonomous nature of his systems, and teamed up with LANL Physicist Brosl Hasslacher to develop the "Mobility, Acquisition, and Protection" space, or MAP for short. Figure 1 is a diagram of MAP from [*6*]

As one might expect from the name, this method uses mobility, acquisition, and protection to measure the ability of an autonomous system to survive in the world.

- *Mobility* relates to the capability of utilizing movement in the environment. M0 implies no motion abilities where as M3 can move in three dimensions, and M- means that external force must be used to move object.
- *Acquisition* relates to the ability to gather, store, and utilize energy. A0 implies zero energy consumption or delivery, A4 means planned tactics used to efficiently extract, store, and utilize external energy, while A- indicates object uses a non-replenishable energy store
- *Protection* indicates the capability to defend oneself. P- indicates one is physically more fragile than the environment while P1 means one executes flight/hide behaviors against hostile stimuli, and P3 demonstrates tactical fight/flight behaviors.

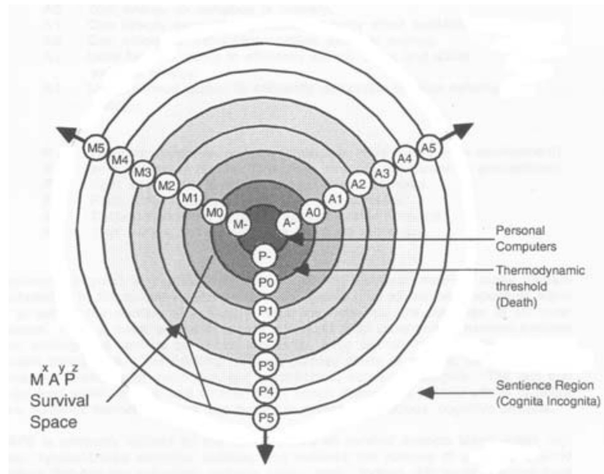

Figure 1: MAP Survival Space in which autonomous systems can be measured

These level metrics are fully described in Table 1 below. The space has three metrics has the three metrics outlines above, and six levels.

Level	Metric: Mobility	Metric: Acquisition	Metric: Protection
" - "	Motion Only Occurs Under Application Of An External Force	Operates from a non-replentishable energy source (battery, power line, etc.)	Negative Defensive capabilities (physically more fragile than the environment)
0	No Motion Abilities	Zero energy consumption or delivery	Zero defensive abilities (structural strength equal to environment
1	Moves Deliberately In One Dimension	Can directly extract/apply external energy when available	Flight or hide behavior against hostile stimulus
2	Moves Deliberately in Two Dimensions	Can effciently extract/store/utilize external energy	Fight or flight behavior against hostile stimulus
3	Moves Deliberately In Three Dimensions	Uses focused tactics to efficiently extract, store and utilize external energy	Tactical fight/flight behavior against hostile stimulus
4	Capable Of dual-mode motion with tools, vehicles, or application of specific design elements	Uses planned tactics to efficiently extract, store and utilize external energy	Too, vehicle, or material use in fight/flight tactics
5	Human	Human	Human

Table 1: Level Descriptors For MAP Survival Space

MAP is actually quite a versatile visual tool, allowing disparate items to be plotted on the same page. Since there are three metrics, one can use a "radar chart" to display the measurements of a particular autonomous system, and this is excellent, since upper management likes radar charts! The Los Alamos researchers also realized this and included a MAP radar chart in their report. Showing this versatility, one can plot an ant, human, and a toaster on the same chart as is done in Figure 2! Tilden and Hasslacher successfully use MAP to illustrate the survival capabilities of the robots they design.

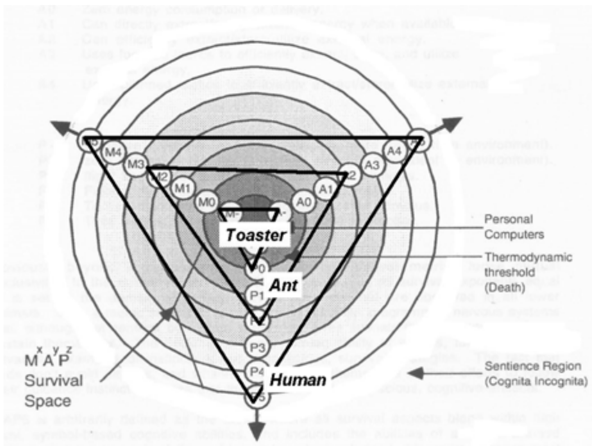

Figure 2: Various Objects plotted in MAP survival Space .

Can this be used to measure the autonomy of UAVs? Possibly. Figure 3 shows a plot of a multi-UAV neural net-based autonomous control system. This plot illustrates the limitations of MAP for our use. All UAVs would score M3 and A- - they move in three dimensions but require stored fuel. Protection ranges between P0 (structural strength to absorb damage) to P4 (groups of UAVs deliberately take out SAM sites). So, is this really useful for FWV autonomy measurement? No.

- Only one axis shows any variability, the others are fixed.
- The metrics just do not address operational characteristics of UAVs. They do not relate the autonomy present in the vehicle to the capability to perform useful missions.
- The metrics do not address interaction between UAVs (teams, swarms, etc.)
- The metrics do not allow us to adequately discriminate between different levels of autonomy. For instance, an RPV and an UAV with autonomy doing the same mission would score the same.

So although using MAP seems to make sense for simple robots, as a UAV autonomy measurement it isn't particularly useful.

So, the first metric space we examined could not fulfill our autonomous control system metric search, so we went on to investigate the other candidate we found – the "3D Intelligence Space" of Charles Stark Draper Laboratory.

2. Draper 3D Intelligence Space

Charles Stark Draper Laboratory (Cambridge, MA) has been developing robotic systems for military and other Federal customers for a number of years. They saw the same need to measure how well their systems could perform various tasks, and developed metrics under the sponsorship of the Office of Naval Research.

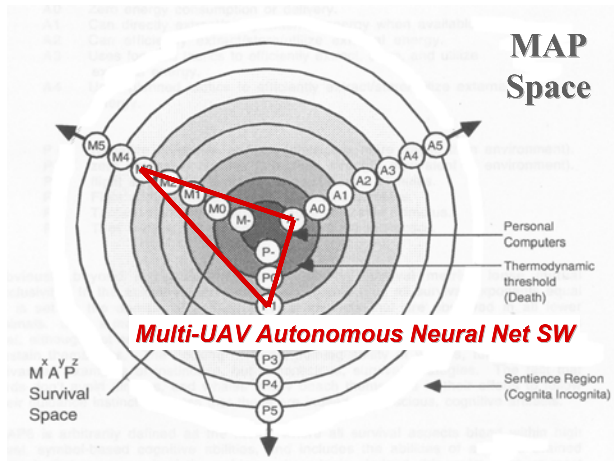

Figure 3: Autonomous Control System Plotted On MAP

These metrics were described in a paper [*7*] written by the Draper Lab researchers last year. This paper contained several different options to measure both intelligence and autonomy. Here we focus on the 3D Intelligence Space outlined in Table 2.

One can see this metric space has a couple desireable attributes:

- It has three metrics,so we can still use three-axis radar charts to represent the results, which will keep management happy(Figure CSD1).
- It has metrics which can be directly related to operational issues.

	Metric		
Level	**Mobility Control**	**Task Planning**	**Situational Awareness**
1	None, RPA Only	None, RPA Only	None, RPA only, or sensor as conduit
2	Operator Assisted	Waypoint or feature oriented	Low-level sensor processing , e.g. visual servoing (template tracking)
3	Get to waypoint, do one feature-based command	Interpret goals into action	Single-Sensor model matching
4	Integrate multiple actions	Multi-Agent Collaboration and C2	Integrated, multi-sensor fusion

Table 2: 3D Intelligence Space

Note that we made the distance between levels in Figure 4 increasing exponentially to represent the difficulties technicallly in going between steps.

We went ahead an plotted the same multi-UAV autonomous control systems used earlier in evaluation MAP space on the Draper radar chart. The results of this are in Figure 5. Note that this simple multi-UAV autonomous control system managed to "max-out" the metric space on all three axes, and highlight the fact that the resolution needs to be better. Other drawbacks include:

- *Task Planning* axis needs to be renamed. Many successful autonomous systems are based on pure reactive behaviors (such as insects). Task planning isn't a prerequisite to autonomy, it just allows better reactions to complicated situations.

- Situational awareness is based on the number of sensors and how they are fused, not on whether or not the autonomous system understands what's going on around it. In other words, this should be a measurement on how well the "big picture" is comprehended and understood.

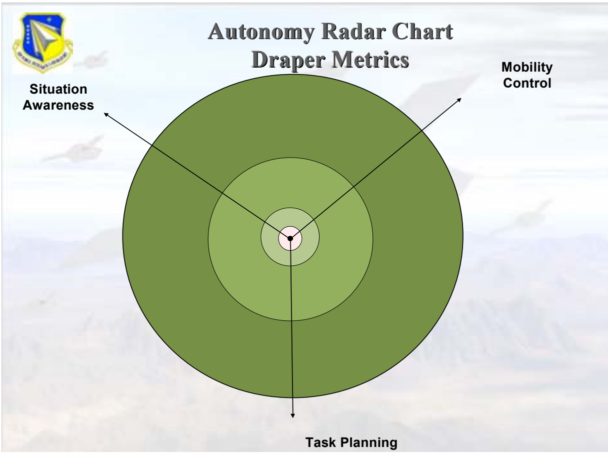

Figure 4: Radar Chart Of Draper Metrics

The drawbacks not withstanding, the Draper metrics provided us another good way of looking at the world.

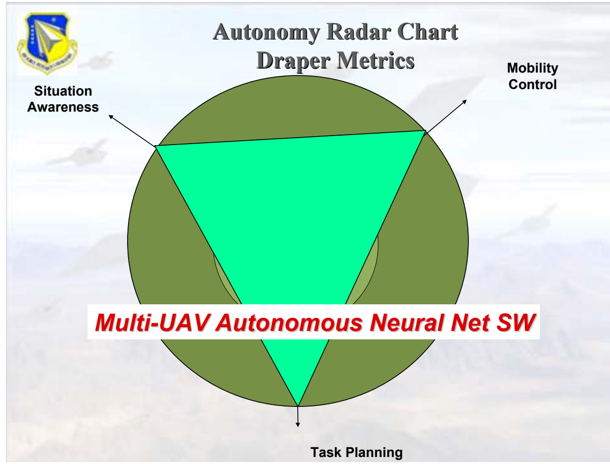

Figure 5: Autonomous Control System Plotted Using Draper Metrics

5. Initial Autonomous Control Level (ACL) Chart

We decided that since no existing metric space existed that could be directly used, we would integrate the best features of the ones we found with what we already used internally to represent where our technology was going. Table 3 is that first cut at an Autonomous Control Level (ACL) chart [Note 2].

Level	Level Descriptor	Perception/Situational Awareness	Analysis/Decision Making	Communication/Cooperation
10	Human-Like			
9	Multi-Vehicle Tactical Performance Optimization	Detection & tracking of other air vehicles within airspace	Full decision making capability on-board Dynamically optimize multi-ship group for tactical situation	Distributed cooperation with other air vehicles On-board deconfliction and collision avoidance Fully independent of supervision/control if desired; No centralized control within multi-UAV group
8	Multi-Vehicle Mission Performance Optimization	Detection & tracking of other air vehicles within local airspace OK to operate in controlled airspace w/o external control	Continuous mission/trajectory evaluation & replan - optimize for current mission situation Avoid collisions and replan/optimize trajectory to meet goals, etc	External supervision - abort/recall or new overall goal On-board deconfliction & collision avoidance Distributed cooperation with other A/V's
7	Real-Time Multi-Vehicle Cooperation	Detection of other A/V's in local airspace Multi-threat detection/analysis on-board	Continuous flight path evaluation & replan Compensate for anticipated system malfunctions, weather, etc - optimize trajectory to meet goals, manage resources, avoid threats, etc	On-board collision avoidance Uses off-board data sources for deconfliction & tracking Hierarchical cooperation with other A/V's
6	Real-Time Multi-Vehicle Coordination	Detection of other A/V's in local airspace Single threat detection/analysis on-board	Event-driven on-board, RT flight path replan - goal driven & avoid threats RT Health Diagnosis; Ability to compensate for most failures and flight conditions - inner loop changes reflected in outer loop performance	On-board collision avoidance Uses off-board data sources for deconfliction & tracking Assumed acceptance of replan; External supervision - rejection of plan is exception Possible close air space separation (1-100 yds)
5	Fault/Event Adaptive Vehicle	Automated Aerial Refueling & Formation sensing Situational awareness supplemented by off-board data (threats, other A/Vs, etc)	Event-driven on-board, RT traj replan to new destination RT Health Diagnosis; Ability to compensate for most failures and flight conditions; Ability to predict onset of failures (e.g. Prognostic Health Mgmt) On-board assessment of status vs trajectory	On-board derived vehicle trajectory "corridors" Uses off-board data sources for deconfliction & tracking External supervision - accept/reject of replan Possible close air space separation (1-100 yds) for AAR, formation in non-threat conditions
4	Robust Response to Anticipated Faults/Events	Threat sensing on-board	RT Health Diagnosis (Can I continue with these problems?); Ability to compensate for most failures and flight conditions (e.g. Adaptive inner loop control); Automatic trajectory execution; On-board assessment of status vs mission completion	Secure, within LOS electronic tether to nearby friendlies Offboard derived vehicle "corridors"; Medium vehicle airspace separation (100's of yds) Threat analysis off-board
3	Limited Response to Real Time Faults/Events		RT Health Diag (What is the extent of the problems?) Ability to compensate for limited failures (e.g. Reconfigurable Control) Automatic trajectory execution	Health Status monitored by external supervision Off-board replan; Waypoint plan upload Wide airspace separation requirements (miles)
2	Pre-loaded Alternative Plans		RT Health diagnosis (Do I have problems?) Automatic trajectory execution (via waypoints) Preloaded alternative plans (e.g. abort)	External commands - alternative plans, approvals, aborts Reports status on request or on schedule Wide airspace separation requirements (miles)
1	Execute Preplanned Mission	Situational awareness via Remote Operator Flight Control and Navigation Sensing	Robotic/Preprogrammed Pre/Post Flight BIT	External control via low level commands Reports status on request Wide airspace separation requirements (miles) No on-board knowledge of other air vehicles - all actions are preplanned
0	Remotely Piloted Vehicle	Flight Control (attitude, rates) sensing Nose camera Situational awareness via Remote Pilot	N/A	Remotely Piloted Vehicle status data via telemetry

Table 3: Initial ACL Metrics Chart

We kept three metrics since we liked the idea of representing systems as areas on a radar chart when briefing management. We added ten levels for better resolution between remotely piloted aircraft and fully autonomous UAVs. The metrics related to operational issues while still being attached somewhat to technological systems. Populating the levels was a group

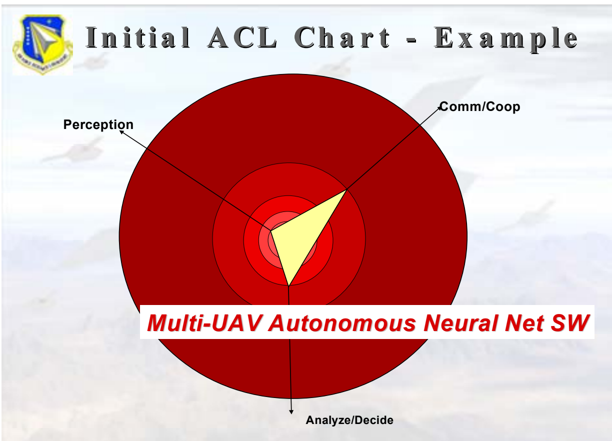

Figure 6: Autonomous Control System Plotted On Initial ACL Radar Chart

endeavor, with a team of researchers, program managers, tech area leads, and contractor experts determining the meaning of each level: "1" was simple – the traditional remotely piloted aircraft (RC-type) while "10" was "human". The trick was populating the eight levels between. As with the Draper metric space in Figure 4 we represented the radar chart as having levels which are exponentially more difficult. We then plotted the same multi-UAV autonomous control system as before, and the result is in Figure 6. We recovered some of the resolution lost in the Draper metrics; however, we still had some issues with the metrics:

- The metrics weren't broad enough to cover UAVs acting on strategic knowledge to achieve strategic results. Our chart limited them to tactical thinking only.
- One metric mixed cooperation with communication – mixing a "what" with a "how".

In general, we tried to stuff as much into three metrics as possible to retain simplicity in briefing presentation and in the process lost the capability to split out issues of multi-UAV control and human-UAV interaction, to name two.

We were going to press ahead and use this metric space when one of the autonomous control system development engineers came up with a good idea [Note 3].

6. If You're Replacing A Human, Why Not Measure Like One?

The great insight was this: we are designing algorithms, agents if you will, to replace pilot decision functions. Machines replace human – so why not look to the human effectiveness community for metrics? Modify the OODA (observe, orient, decide & act) loop - originally developed to show how to get inside your enemy's decision loops - [*8*, & Note 4] for our use, and populate the levels with modifications of the qualifiers of the initial ACL chart. Table 4 is what we developed using this insight. The same team of experts that developed the initial ACL chart also worked on the new ACL chart to ensure consistency with earlier thoughts. We lost the three axes representation, which means we lost the ability to generate the "simple" radar charts which makes management happy; however, we gained better resolution between metrics which, at least in our thoughts, more than made up for that.

Since we have developed the ACL chart, we've used it to both assess the current UAV efforts, and to extract from that where our own technical efforts must go. Nationally, we've developed time-phased autonomous system goals to put our autonomous systems roadmap together. The ACL has been published as part of the DoD UAV Roadmap [*9*], and other DoD Labs use it to measure their autonomy development. Locally we've developed technical area roadmaps putting programs together to meet the time-phased ACL goals. The ACL chart also acts as a program advocacy tool, allowing us to show management how each program fits into increasing ACL capability for each metric, and also how each program investment integrates into the national strategy. Our experience from using it for one budget planning cycle has been very positive:

- Once management was briefed on the chart and it's development (and some in management had ownership in it's development) it was accepted as the tool to measure program goals.
- It provided clear indications of where the technology was targeted and what national goal it met, allowing better informed budget planning decisions.
- We have common ground for talking amongst other Federal technology development organizations, universities, and industry. Each of us has a much clearer picture as to where technological programs fit.

7. Summary

Our work with autonomous UAVs indicated to us that we needed metrics to measure the progress of our programs building that autonomy. The same issues existed on a national level, so we decided to develop metrics for the national-level effort, then apply those to our local program planning process.

Our literature search for autonomous system metrics only returned two references for metrics. Both we examined and used on an example problem. Although each wasn't directly applicable, concepts of each, integrated with our own existing ideas, formed an initial ACL chart. This chart was modified based on concepts human dynamists had developed - specifically the OODA loop. The resulting set of metrics captured our original intent. [*Note 4*]

Since development, the ACL metrics have been used successfully at the Air Force Research Laboratory in developing plans and programs in autonomous UAV controls research. The ACL chart is in current review at DOD levels to be applied across the services as part of the FVW initiative. With this development we are pressing ahead in the assessment of possible sub-metrics to better hone our program planning.

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9. Notes

1. Not that we didn't have any. We had already split autonomy into four levels depending on the amount of human interaction and where it occurred. These are:

- Remotely Piloted: The UAV is simply a remotely piloted aircraft with the human operator making all decisions.
- Remotely Operated: The human allows the UAV to do the piloting, but outer loop decisions are made by the human (like where to go and what to do once there). The UAV is a "mother-may-I" system, asking the human permission to do tasks.
- Remotely Supervised: The human allows the UAV to execute its own tasks, only taking command if the UAV fails to properly execute them.
- Fully Autonomous: The UAV receives goals from the humans and translates that into tasks which it does without human intervention. The UAV has authority to make all decisions.

2. Most of the grunt work in putting the chart together was done by Dan Thompson, AFRL/VACC, and Dr. Alan Burkhard, AFRL/VAC - the rest of us got to snipe at it.
3. The researcher's name is Bob Smith, and besides coming up with decent ideas he also has developed a formation flight agent for UAV formations which uses a blend of deliberate and emergent behavior.
4. Boyd's OODA loop, originally developed to illustrate how to take advantage of an enemy, has been grasped wholeheartedly by business management folks. The observe, assess, design, and act (OADA) loop organizational dynamists use to explain how decisions are made is a direct descendant.
5. I know, you're wondering about Sheridan's Autonomy Levels. Truth of the matter is that if you search for "autonomy", "metrics", "measuring autonomy", etc., you don't run into Sheridan. Had I searched using "teleoperation" I would have found the Sheridan Autonomy Levels [*11*].

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

Table 4: Final ACL Chart