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Autonomous System Reference Framework and Early Design Decisions

Rosteslaw Husar*, Jerrell Stracener**

Abstract

System autonomy assessment tools and methodologies are not consistent across the Department of Defense (DoD). The Defense Science Board was tasked to review current "Levels of Autonomy" assessment methods and concluded that they are counter-productive to the autonomy design process as the focus is on the computer and not on the collaboration between the computer and its operator/supervisor. The Defense Science Board recommended that the DoD abandon the debate over definitions of levels of autonomy and embrace a three-facet Autonomous Systems Reference Framework to replace "Levels of Autonomy". We developed our contribution to such a framework and described it in this paper.

Keywords: Systems Engineering, Autonomous Systems, Requirements Engineering, System of Systems Component, System Autonomy Modeling

1. Introduction

The development and design of autonomous systems is a new technological field experiencing rapid growth in part due to the proliferation of drones, robots and unmanned systems. The rapid growth has presented several technical issues which have been cited as impediments to the acceptance of autonomous systems. Major issues and possible barriers to the development of future autonomous systems were identified and detailed in reports issues by the U.S Navy's Chief of Naval Operations Strategic Studies Group (SSG) XXVIII (Hogg, 2009) and by the Defense Science Board (DSB) (Kaminski, 2012) of the U.S. Department of Defense (DoD). Several major misconceptions and technical issues as significant barriers to development and adoption of autonomous systems were identified by the DSB and SSG. Those reports outlined a potential reference framework to help align and coordinate future developments. This paper presents methodologies to support an Autonomous Systems Reference Framework and focuses on the very early stages of concept definitions and developments.

Those DoD reports identified barriers to autonomous systems development that included the following areas:

- Inconsistent rule sets/ requirements of autonomous systems,
- Inconsistent measures/ metrics of autonomous systems,
- Inconsistent trade off studies and analyses of autonomous systems,
- Inconsistent systems engineering development processes of autonomous systems,
- Inconsistent applications of autonomous systems, and
- Inconsistent test and evaluation of autonomous systems.

The common definition of autonomous systems provided by the Office of Secretary of Defense are that autonomous systems are supervised by human operators at some level, that autonomous systems needs to be considered in terms of human-system collaboration, abandon the debate over definitions of levels of autonomy iorfavour of a multi-faceted autonomous systems framework (Kaminski, 201; (Hogg, 2009). Our methodology supports the Autonomous Systems Reference Framework (ASRF) by developing

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* Southern Methodist University United States Email: rustyhusar@gmail.com

** Southern Methodist University United States Email: jerrells@lyle.smu.edu

an algorithmic relationship between human interaction and machine automation that replaces the "Levels of Autonomy" and facilitates multi-dimensional trade space analyses not previously obtainable.

The development of requirements, Analysis of Alternative (AoA), Concept of Operation (CONOPS), Life Cycle Support Analysis are among the major activities during the very early design phases. An autonomous systems assessment methodology that allows the relative comparison of human interaction-machine automation between candidate system concepts is needed to support those engineering design activities.

2. Background

The United States Department of Defense (DoD) is facing declining defnsce budgets for at least the next several years while adversary nation experience double digisedefence budget increases 1. In this fiscal environment, the DoD must find new ways in meeting the goal of providing national security. A significant portion of the budget is for manpower in the operations and support phase of the system life cycle. Unmanned autonomous systems can provide this force multiplier 2 (Deyst & Egan, 200; (Murphy & Shields, 2012). Autonomy for unmanned systems is the needed technological innovation to reduce the workload of human operators. This technological demand is greatest in military operations where significant loss of life and extreme hazardous situations are common place.

Unmanned vehicles are a key component of the U. S. Navy (USNsedefence transformation (O'Rourke, 2006). The USN has several programs under development to address reduced manning with increased use of unmanned vehicles (UxV) (Stone, 2012). These unmanned vehicles require a significant amount of human interaction (HI) to control the UxV and interpret a significant amount of down linked data. Assessing intelligence, surveillance and reconnaissance (ISR) data to develop actionable security operations will continue to be a national priority. The amount of data collected is overwhelming the analysts. Current state of the art unmanned systems, like the Predator Unmanned Air Vehicle, require a sizeable team to operate the air vehicle, interpret sensory information, dynamically assess mission impacts and execute missions. The increasing demand for ISR missions are increasing crew support, counter to declining budget trends.

2.1. Defnsce Budget Constraints

The Congressional Budget Office in their FY2014 report anticipates that the portion of Gross Domestic Product (GDP) dedicated to the DoD will continue to decrease over the next several decades (Elmendorf, 2013). Future reduced funding for systems development will take a larger share of the operations, maintenance and personnel costs within the constrained budget.

To address this environment of declininsedefence budgets concurrent with increasing threats, the U. S. Navy is implementing unmanned technology in meeting the goal of providing national security at reduced cost (Kaminski, 2012). Autonomy is the needed technology to reduce manpower by allowing a single operator to manage multiple unmanned systems.

Autonomous systems results from complex integration of human intelligence and machine automation capable of adapting to unforeseen events (Kaminski, 2012). Autonomous systems could operate more independently and with lower focus levels of human interaction (HI), thus allowing for significant reductions in manpower.

The USN has several programmes under development to address reduced manning through increased reliance of unmanned vehicles (UxV) (Stone, 2012) and these systems require ever increasing levels of complex automation and autonomous capabilities. Proposed near-term maritime missions involve the use of collaborative unmanned autonomous systems.

2.2. Information Technology Acquisition Changes

The 2009 & 2011 U.S. National Defense Authorization Acts, Sec 804, mandated a new Information Technology (IT) Acquisition Process 1Figure 1 (Pontius, 201),

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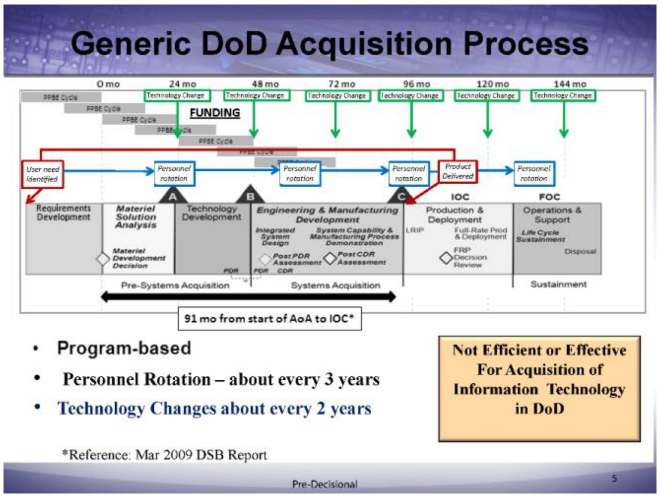
1 Karl Ritter, April 15, 2013, The World Post and the Stockholm International Peace Research Institute (SIPRI)'s Year Book 2013 summary on military expenditure reported defense budget increases for China of 325%, Russia of 179% and South Korea of 59%.

2 A capability that, when added to and employed by a combat force, significantly increases the combat potential of that force and thus enhances the probability of successful mission accomplishment. http://www.military-dictionary.org/force_multiplier

was required because the defnsce acquisition process structured for weapon systems was ill-suited for information technology. Those IT systems take too long to deliver and the process was documentation intensive. The current acquisition oversight process was not aligned with rapid acquisitions and favoured large programs with high-level oversight. The complexity inherent in aligning the three major DoD processes of requirements, resourcing and acquisition was also a barrier.

Figure 1: Long System Acquisition Cycle



Generic DoD Acquisition Process

- Program-based
- Personnel Rotation – about every 3 years
- Technology Changes about every 2 years

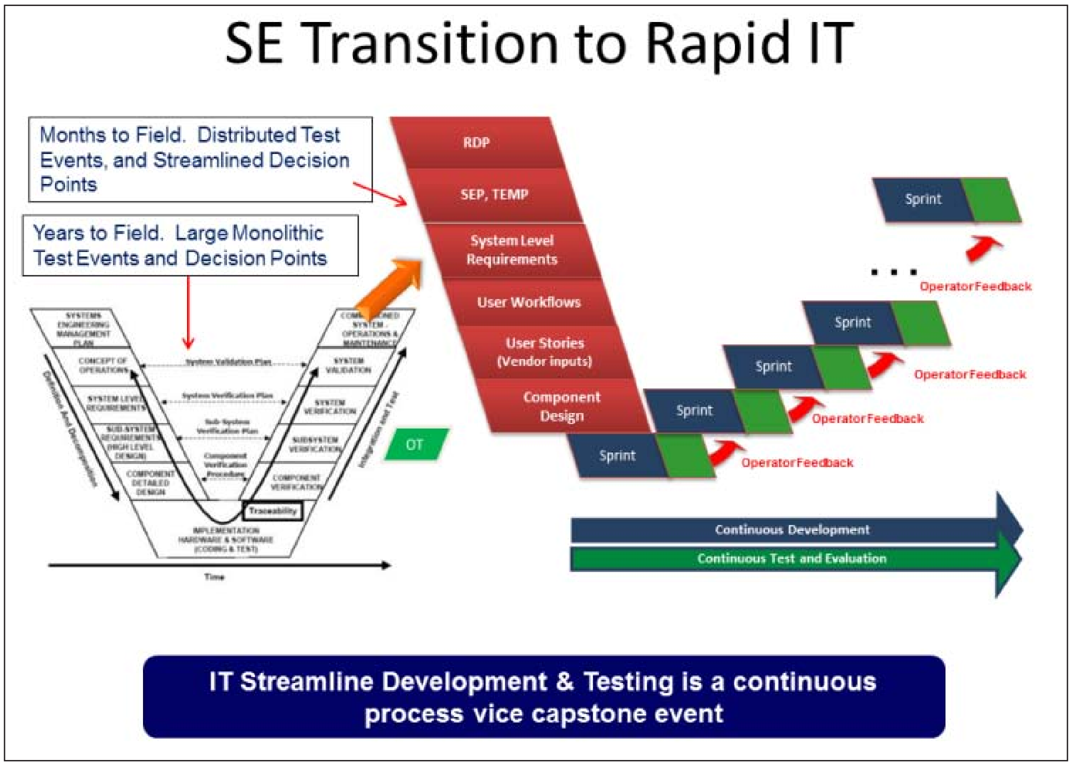
Not Efficient or Effective For Acquisition of Information Technology in DoD

*Reference: Mar 2009 DSB Report

2.3. Systems Engineering Process Changes

What is common across these acquisition processes is the need to develop the "best" end product in response to a set of needs. This can be accomplished by execution of the systems engineering process where the requirements analyses and the allocation of those requirements are performed (Director, 2008). Integrated tools to support analyses and assessments are critical at this early design phase because any shortfalls or miscalculations become costly if carried through the life cycle (Acquisition, 2009). The AGILE methodology 3Figure 2, is such an engineering process and focuses more on the collaborative efforts between the software developers and 'customers' to allow for early capability releases(Douglass, 2012) (IBM, 2013). As a result, the releases are time driven rather than event driven which allows for maturing of the capabilities based on 'customer feedback'. This accelerated and iterative development release model is reliant on rational tools to support system analyses and requirements trade off studies as design deficits or errors become costly at later stages of the product life cycle. The AGILE methodology is appropriate for capabilities reaizsed by software rather than implemented by hardware, which requires longer procurement and fabrication cycles (Douglass, 201)(IBM, 2013).

Figure 2: AGILE Design V



SE Transition to Rapid IT

Months to Field. Distributed Test Events, and Streamlined Decision Points

Years to Field. Large Monolithic Test Events and Decision Points

IT Streamline Development & Testing is a continuous process vice capstone event

3. System Autonomy Assessment

While often interchanged, 'automation' and 'autonomy' are not synonymous and what is frequently referred to as a 'Level of Autonomy' (LoA)*'is a combination of human interaction and machine automatio 5*] (Hogg, 2009). The SSG continues to state that *'the degree of machine automation is not easily categoizsed'* and not fully *'understanding autonomy has hindered development'* of unmanned systems in the Navy.

Figure 3: Sheridan Scale

High	10	The computer decides everything, acts autonomously, ignores the human
	9	Informs the human only if it, the computer, decides to
	8	Informs the human only if asked, or
	7	executes automatically, then necessarily informs the human, and
	6	allows the human a restricted time to veto before automatic execution, or
	5	executes that suggestion if the human approves, or
	4	suggests one alternative
	3	narrows the selection down to a few, or
	2	The computer offers a complete set of decision/action alternatives, or
Low	1	The computer offers no assistance, human must take all decisions and actions.

As DoD acquisitions favour decreasing and rapid development cycles (Pontius, 2012), the ambiguity in defining system autonomy, machine automation and human interaction contributes to alternate architecture assessment and trade studies leading to ambiguous requirements development.

3.1. Requirement for an ASRF

The Defense Science Board Task Force (Kaminski, 2012) and the Strategic Studies Group XXVIII (Hogg, 2009) were specifically tasked to focus on autonomous systems for military applications. The Strategic Studies Group (SSG) was issued in 2009 and many of the observations and recommendations were also found in the Task Force Report.

The Final Report of the Defense Science Board (DSB) Task Force on the Role of Autonomy in Department of Defense (DoD) Systems was release on 19 July, 2012. The DSB reviewed many DoD funded studies on LoA and concluded that they are not particularly helpful to the autonomy design process'. Those studies *tried to aid the development process by defining taxonomies and grouping functions needed for generalized scenarios*. However, they were found to be *counter-productive because they focus too much attention on the computer rather than on the collaboration between the computer and its operator/supervisor*. The competing definitions for autonomy have led to significant misunderstanding among developers and operators (Kaminski, 2012). *An equally unproductive course has been the numerous attempts to transform conceptualnsations of autonomy made in the 1970s… of Sheridan's early wor*] (Figure 3) *for the National Aeronautics and Space Administration (NASA) …and is often incorrectly interpreted as implying that autonomy is simply a delegation of a complete task to a computer, that a vehicle operates at a single level of autonomy and that these levels are discrete and represent scaffolds of increasing difficulty. Not developing a capability through the best combination of human and machine abilities - foster brittle designs resulting in additional manpower, vulnerabilities and lack of adaptability for new missions.*

The DSB held that it should be made clear that all autonomous systems are supervised by human operators at some level, and autonomous systems' software embodies the *designed limits on the actions and decisions delegated to the computer…the reality of what autonomy is and can do is quite different from those conjured images, these concerns are - in some cases - limiting its adoption.* Rather than viewing autonomy as an insular, intrinsic property of unmanned vehicles, the design and operation of autonomous systems needs to be considered in terms of human-system collaboration.[(This would represent the first requirement in developing a system autonomy assessment tool in support of requirements development; R1 – Human-Machine collaboration shall be considered in the design of autonomous system]).

The DSB stated that the DoD should abandon the debate over definitions of levels of autonomy and create an Autonomous Systems Reference Framework to Replace LoA, see Figure 4 [(R2 - Autonomous Systems Reference Framework shall replace 'Levels of Autonomy)].

During the early design phases of autonomous system, a number of important decisions are made to allocate specific cognitive functions to either the computer or the human operator/supervisor. These decisions reflect system-level trade-offs between performance factors, such as computationally efficient, optimal solutions for expected scenarios versus susceptibility to failures or the need for increased manpower when off-plan situations occur. The DSB went on to state that Autonomy is, by itself, not a solution to any problem. The utility of an autonomous capability is a function of the ecology of the specific mission needs, the operating environment, the users and the vehicle - there is no value without context. The expectation that autonomy can be added to fix unmanned vehicle design deficits without considering the larger system is flawed [(R3 - Autonomous Systems Reference Framework shall consider system of system and mission context contribution)].

The current LoA taxonomies are misleading both from a cognitive science perspective and from observations of actual practice… system autonomy is a continuum from complete human control of all decisions to situations where many functions are delegated to the computer with only high-level supervision and/or oversight from its operator.([R4 – System Autonomy is the continuum from complete human control to operator oversight of machine delegated functios]). Multiple concurrent functions may be needed to implement desired functions requiring a human in the loop, while other functions may not. Thus, at any stage of a mission, it is possible for a system to be in more than one discrete level simultaneously…and… treatingLoA as a developmental roadmap has created a focus on machines, rather than on the human-machine system.

The complex system trades, in which choices about where and how to inject autonomy, are made, explicitly or implicitly, in all designs, and the Task Force recommends that they be an explicit part of the requirements, design and review process. System trades made without explicit awareness of their respective implications can lead to many unintended consequences, including higher manpower and training costs, avoidable collateral damage, failures attributed to "human error" and underutionsation [(R5 – system autonomy trade studies shall be part of requirements desig)]. Because the DoD has limited experience with the new capabilities autonomous systems provide, requirements definition and acquisition processes have been difficult. No unmanned, autonomous systems have formally completed operational test and evaluation (OT&E) prior to being released to the field. This has implications on the methodologies for validation and verification of any Autonomous System Reference Framework.

Unlike other defnsce systems, the critical capabilities provided by autonomy are reaizsed by the system software. In contrast, the traditional acquisition milestones for unmanned systems are dominated by hardware considerations. Autonomy software is frequently treated as an afterthought. To address this situation an autonomy reference framework should be used throughout the requirements definition and design phases of autonomous systems development programs [(R6 – Autonomous Systems Reference Framework shall support requirements trade studies throughout the design life cycl)].

Figure 4: Framework for the Design and Evaluation of Autonomous Systems

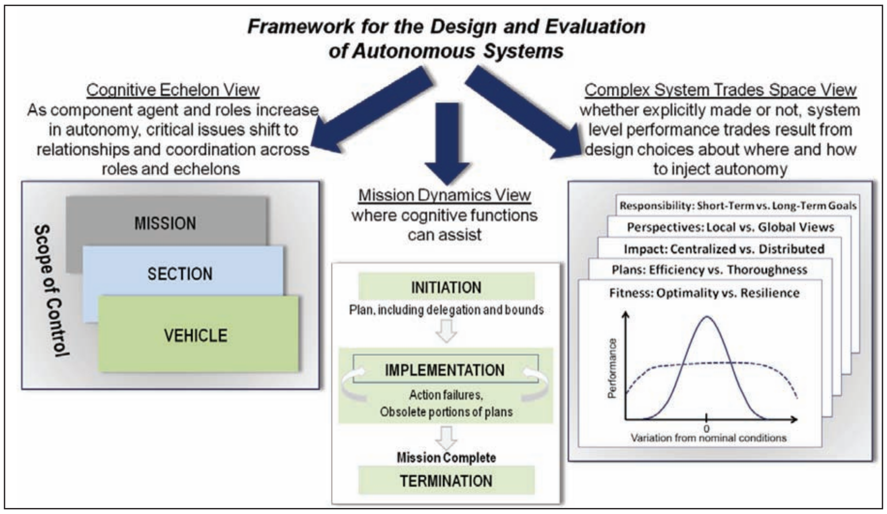
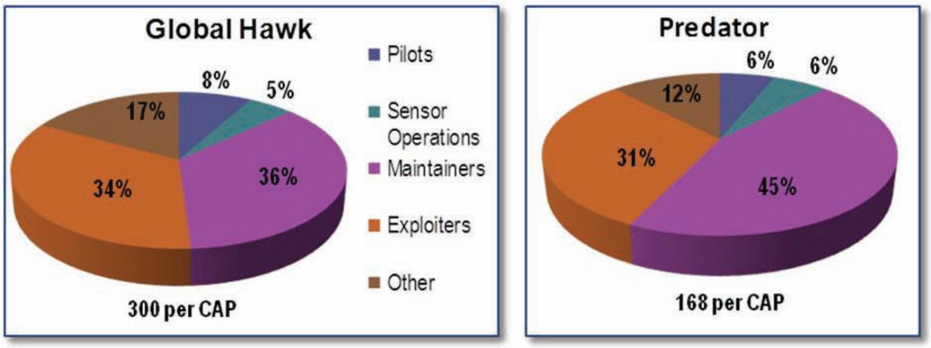


Figure 5: Manning Unmanned Platforms is a Key Staffing Problem



The DSB expressed concern regarding an adversary's use of autonomous systems. The DSB identified that benefits of using unmanned vehicles to conduct intelligence, surveillance and reconnaissance (ISR) missions in contested areas are broadly understood and, as a result, over 50 countries have purchased unmanned surveillance vehicles, and the international market for the technology is very robust. Research and demonstrations related to intelligent robots are common undergraduate projects in universities worldwide. The ubiquity of unmanned systems technology, combined with potential adversaries who might be less concerned with rules of engagement and collateral damage or are capable of applying advanced software concepts already in the scientific literature, could result in a range of challenging threats. (R7 - Autonomous Systems Reference Framework shall be capable of assessing adversarial capabilities). Adversary applications of this technology include significant harassment on the battlefield, low intensity adversary surveillance prior to transition to hostile action and asymmetric attacks on the U.S. homeland.

Autonomy will vary with the types of decisions being made that decision types change over the timeline of a mission. A typical mission may have an initiation phase followed by an implementation and termination phase. Each phase represents a different opportunity for autonomy. (R8 - Autonomous Systems Reference Framework shall be capable of assessing temporal system autonomy). For example, the initiation phase may require a specific level of autonomous operation during the preparatory and prelaunch phase of a mission; transitioning to autonomous waypoint navigation and monitor for changing situations which may render portions of an initial plan obsolete, require re-planning; a termination phase may specify a level of autonomy to preprocess collected data and return the vehicle home and land.

Human-Machine trade space view is helpful tool for predicting unintended consequences and linking symptoms of imbalances (higher manpower, breakdowns, increase in human error, etc.) with the source. (R9 - Autonomous Systems Reference Framework shall be capable of parametric sensitivity analysis). Potential warning signs of an imbalance in this trade space could be surprisingly higher manpower, lower reliability and creeping complexity costs. The example provided by the DSB was how the UAV CONOPS changed with an expectation of 20 orbits, to a demand for with 85 orbits which have exceeded the designed capacity, resulting with a manpower growth to 170 people.supporting a combat air patrol (CAP). Fig, 5 shows the number of human operators required per CAP for The Global Hawk and Predator. Although these systems are highly automated, a high level of human supervision is required to achieve the system autonomy needed for mission success. The human-robot interaction is a relatively new field addressing how people work with robots, rather than computers or tools, with the focus on bi-directional, cognitive. (R10 - Autonomous Systems Reference Framework shall be capable of relating Human Interaction and Machine Automation to System Autonomy).

3.2. ASRF Outline

A system autonomy assessment tool must show a mathematical relationship between human interaction and machine automation (Kaminski, 2012). Being a software only model, this tool would be a good candidate for the AGILE development methodology. The AGILE approach would allow early deployment of ASRF capabilities while maturing other for later deployment (Douglass, 2012; IBM, 2013). A workable and measurable definition of system autonomy (SA) is then defined as a functional of human interaction (HI) and machine automation (MA):

$$SA = F[MA, HI] \tag{1}$$

If System Autonomy is considered as a vector, then the relationship between HI and MA would provide the scalar component. Mathematical assessment of SA as a vector representation is far more logical than using discrete integer levels.

The many unmanned air vehicles requires different levels of human interaction and supervisory control. Unmanned Air Vehicles range in sophistication and may need one or more human supervisors to successful carry out a surveillance mission. Equation 1 describes a single operator, single UMS configuration; the SA function from equation 1 above is modified as follows:

$HI = G[HI_1, HI_2,\ldots HI_n]$, where n is the operators needed during the mission (2)

An alternative design for the system autonomy equation is a network of unmanned vehicles controlled by a single operator. This increases machine automation and facilitates a network of multiple UMS, operating concurrently and is supervised by a single controller. The alternate design would have multiple UMS operating sequentially and supervised by a single controller.

As the number of intelligence, surveillance and reconnaissance (ISR) missions increase, a single operator would control multiple UMS and in this scenario the equation is modified as:

$MA = K[MA_1, MA_2\ldots MA_m]$, where m is the number of UMS (3)

3.2.1. System Autonomy as a Vector

Figure 6 graphically depicts System Autonomy as a vector in the MA/HI trade space. The magnitude of the SA vector is determined from the contributions of MA and HI component variables. The magnitude indicates whether the system architecture would meet mission objectives. The significance of the angle is discussed later. When the required value of the vector SA is set to a constant throughout the trade space, this defines the minimum autonomy levels needed to meet mission requirements. The dotted arc represents the Minimum Capability Threshold (MCT) where SA would meet this threshold. If the magnitude of the candidate system vector fell short of the MCT, then some mission objectives would not be accomplished.

Additional contributions from MA and HI would be needed to increase the magnitude of the SA vector. Magnitude exceeding the MCT indicates more than needed system autonomy to execute the mission. Normaizsing the SA vector to a value of one (SA=1) allows further investigation to the relationship between MA and HI. Setting the SA vector to intersect with the HI axis sets the value for MA = 0 and HI = 1. This represents complete machine dependence on human interaction. Setting the SA vector to intersect with the MA axis sets the value for MA = 1 and HI = 0. This represents complete machine independence from human interaction. Maintaining SA=1 as the vector moves within this plane scribes the MCT arc and provide the mathematical relationship between SA, HI and MA. This spare capacity can be viewed as capability reserves or targeted for reduction as potential life cycle cost efficiencies. The magnitude of the vector becomes

$$SA = \surd(HI^{\wedge 2}+MA^{\wedge 2}) = F[HI,MA] \tag{4}$$

This allows the relationship between MA and HI to be defines as:

$$HI=\surd(1+MA^{\wedge 2}) \tag{5}$$

Treating SA as a vector allows for analysis of candidate systems during the AoA and concept of operation activities where the systems design is developed.

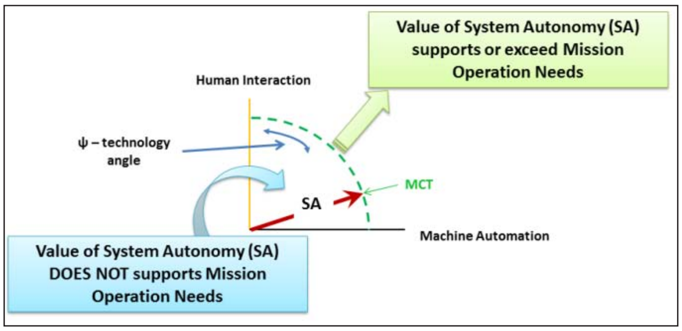
3.2.2. SA Phase Angle

The angleΨ, (Figure), provides an indication of the technology inherent in the configuration. The angle, with the scalar magnitude, describes SA as a vector. This allows vector mathematics when assessing system of autonomous system configurations. The angle is expressed as:

$$\Psi= \tan^{-1}[MA/HI] \tag{6}$$

The SA phase angle provides a relative comparison of the technology base for the candidate system. The smaller the difference in angles indicate that the candidate systems share the similar technology architectures and comparative analysis is relative straight forward. The greater the difference between the phase angles indicates that the systems have a diverse technological base making any comparison more complex.

Figure 6: System Autonomy Trade Space



$$\overline{|SA|} \overset{\text{def}}{=} \sqrt{(MA^2 + HI^2)}\ and\ \tan^{-1}(\qquad (7)$$

3.1.3. System Autonomy Trade Space

Expressin identifies the magnitude and phase angle of the vector. This provides the algorithmic assessment capabilities the current methods cannot provide.

Figure 7: Diverse Technologies

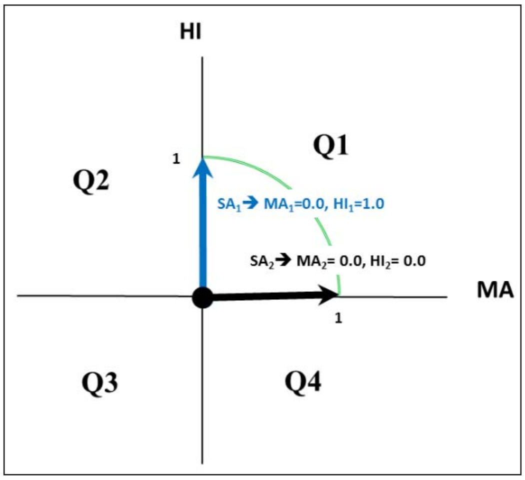


Figure 7 Figure magnitude. Both systems meet the MCT but the difference between the Ψs is 90^{o} and indicates an extreme divergence of technologies. One system is tele-operated, Level 1. The other system exhibits android behavior, Level 10 and does not depend on any human interaction (Parasuraman *et al.*, 2000). A comparison between the two systems architectures would not be straightforward because they operate in significantly diverse manners.

For clarity, a systems candidate is shown in quadrant (Q1) unless uncooperative assessments are needed. Systems in different quadrants have vector components that would tend to negate, resulting in a smaller magnitude value. Systems in Q3 would be considered as countermeasures to systems in Q1 and are diametrically opposing forces. Systems in Q2 and Q4 have utility and assessments that may include fault, stress test or destabilizing scenarios.

Future missions would include collaborative operations of more than one unmanned vehicle and the equation would be expanded to have two or more unmanned systems, UMS;

$$SA = F[SA_1] + F[SA_2] + \ldots F[SA_k] \text{ where k is the number of UMS} \qquad (8)$$

Collaborative missions would include mixed UxV modes such as surface (USV), ground (UGV), air (UAV) and underwater (UUV) contributions. In the above relationship, UxV would be substituted by the appropriate type and number of UAVs, USV, UGVs and or UUVs as identified by the mission requirements. If one operator controls multiple UxVs, then the variable permutations of this model grow in complexity and a clear need for a model and methodology during AoA and CONOPS development becomes evident. The multiple combination UMS equation for SA becomes:

$$SA = F[SA_{UAV}] + F[SA_{UGV}] + F[SA_{USV}] + F[SA_{UUV}] \qquad (9)$$

Inclusion of dynamic variables like mission difficulty, meteorological impacts and many other probabilistic variations just increases the complexity of understanding and defining requirements.

3.1.4. Contextual System Autonomy

In previous sections, System Autonomy was discussed as a two dimensional vector. In more representative scenarios, system autonomy, human interaction and machine automation vary throughout the mission. Varying machine automation to meet mission needs is currently possible by commanding the machine to perform less than its maximum design capabilities allow. In some cases, new software can be downloaded to perform more efficiently. If the capability is not mechanically inherent in the machine, hardware reconfiguration by the machine itself is not supported by current technologies. The same may not be true of the human interaction element.

Figure 8: Contextual Autonomy

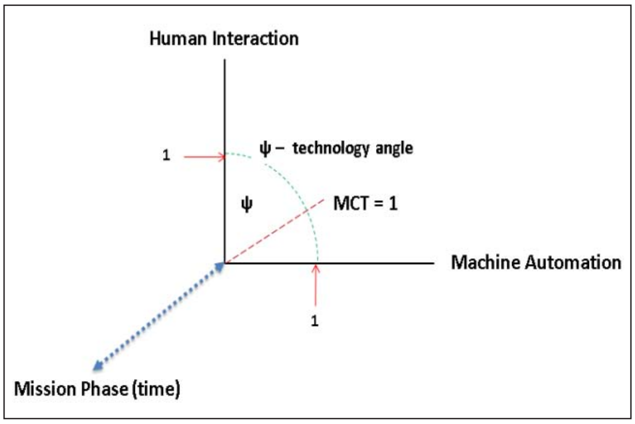


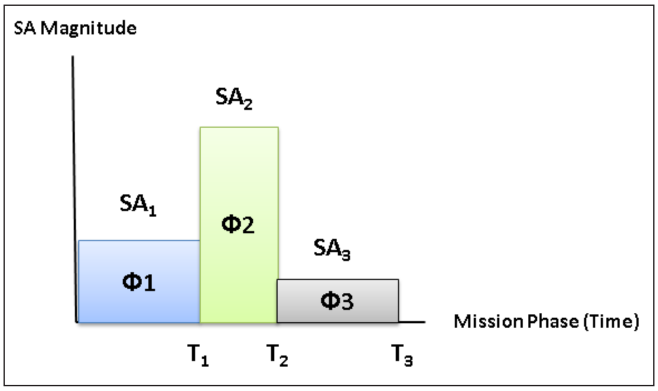
Figure 8 provides time as the third dimension to the trade space. Expanding the trade space to a third dimension should not infer a three dimensional SA vector. Instead the magnitude of the two dimensional SA vector is plotted against the third axis which represents the mission time. The mission phases may evolve and require a change from one type of UMS to another or a change of operator skills. In this case a Mission Phase would describe the system autonomy needed to conduct the mission phase peculiar activities. Mission Phase changes can appear as discontinuities in the SA level.

Mission Phase

Time becomes a consideration in two ways. Complex mission scenarios may require several changes of system autonomy levels due to the changing phases of the mission like transit and area surveillance. This causes the SA vector to have a Mission Phase dependency. The combination of human supervision/interaction and the level of needed machine automation may need to vary within each discrete mission phase. This causes the SA Vector to have a time variant dependency.

Figure 9 graphically represents the two dimensional SA vector throughout the notional mission duration. In this example, mission scenario with three phases – Φ1 is the transit to operation area, Φ2 is the surveillance and reconnaissance and data gathering activity and Φ3 is the return transit. Each of these mission segments may require a specific level of SA. In this depiction, each SA is constant through the mission phases. This is not typical and most often observed is that there is some SA level variability with each mission phase.[3]

Figure 9: Mission Phase



4. Comparative Autonomy Assessments

In 2007 Southwest Research Institute(McWilliams, 2007), applied the Autonomy Levels for Unmanned Systems (ALFUS) framework to assess the achieved autonomy levels of eight unmanned ground vehicles (UGV), see Table 1. ALFUS is a framework that has been developed by a consortium of government and non-government agencies during several workshops. Note that in the ALFUS methodology, the variable HI* is Human Independence. The UGVs were categorized into four groups by market area and use. This allowed some narrowing of the definitions of Mission Complexity (MC) and Environmental Difficulty (ED) within each group. Even with this pre-filtering, some ambiguities in assessment existed and straight comparisons outside of the grouping are not straightforward. Within the Passenger Vehicle grouping, both UGVs require a human operator. In several of the UGVs, the human operator actuated the throttle and brake but not steering or needed to monitor the UGVs unsafe lane positions and distances to vehicles. The ALFUS HI* does not portray the involvement of the human operator as he would be required 100% of the time during these tests. Using the ALFUS framework, SRI assessed the MC, ED, HI*,∑and average ∑ for each UGV within the specific group constraints. The mission complexity includes terrain and hostilities in the case of the Military grouping which spills into the environmental difficulty which also take into account terrain and hostilities. When SRI summed the three variables, the ALFUS autonomy assessments of the UGVs were very similar.

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[3] This is the author's observation in working with ISR UUVs, Anti-Torpedo-Torpedo, Littoral Combat Ship Mission Packages, several Mine Neutralization UUS and missile and torpedo programmes.

Table 1: SRI ALFUS Assessment

		SRI/ALFUS				
Category	UGV	MC	ED	HI*	Σ	*Average Σ*
Passenger Vehicles	NavLab	4	7	6	17	*5.67*
	ARGO	4	7	8	19	*6.33*
Transit & Frieght	CMU Houston Metro Bus	5	3	8	16	*5.33*
	CyberCars	6	5	10	21	*7.00*
ET Rover	Spirit	6	7	6	19	*6.33*
Military	XUV DEMO III	6	6	9	21	*7.00*
	Crusher	7	7	7	21	*7.00*
DARPA Grand Challenge	Stanley	4	6	10	20	*6.67*

In the ALFUS methodology, the variable HI* provides for human independence. If this variable is viewed as a form of machine automation (MA), then the algorithmic assessment can be applied, see Table 2. The algorithmic value of human interaction (HI) and the technology base angle (Ψ) are calculated for each UGV using Equations 7 and 8. Although human operators were needed to operate some of the UGVs, adjustments must be made to the ALFUS levels. In the case of the NAVLAB UGV, the researchers operated the throttle and brakes manually thereby increasing the human interaction to a greater level than indicated by ALFUS.

When the UGVs are further segregated into subgroups, the algorithmic assessment in Table 2 shows that the technology bases of the UGVs within each grouping may be too diverse for straight comparisons. Comparisons of those UGVs with similar Ψs are straight forward and other factors such as life cycle cost can be compared. Performance attenuating parameters such as terrain difficulty or hostilities can be applied in stochastic studies in developing concept of operations. The ALFUS methodology provides a combined "Level of Autonomy" label assessment and parametric sensitivity studies could not be performed easily.

In the analysis performed by SRI, the three ALFUS variables were summed and identified as ∑. An alternate assessment of MA is done if the ALFUS variables are averaged and then applied as MA in a similar fashion done by SRI. As was found in the SRI assessments, the Ψs of the UGVs become numerically closer, indicating relatively straightforward comparisons are possible. A more detailed assessment of the UGV ALFUS assessments, outside this scope of this paper, would provide more accurate system autonomy valuations. As in the previous case, factors such as life cycle cost can be included for comparison. Parametric sensitivities and stochastic modeling can be performed to contribute to AoA, CONOPS and requirement development are not possible with the ALFUS framework.

Table 2: Algorithmic Assessment of UGVs

		MA & HI Adjust			
Category	UGV	MA	HI	SA_C	Ψ_C
Passenger Vehicles	NavLab	0.70	0.90	1.14	37.87
	ARGO	0.70	0.50	0.86	54.46
Transit & Frieght	CMU Houston Metro Bus	0.70	0.50	0.86	54.46
	CyberCars	0.90	0.10	0.91	83.66
ET Rover	Spirit	0.50	0.90	1.03	29.05
Military	XUV DEMO III	0.70	0.10	0.71	81.87
	Crusher	0.70	0.10	0.71	81.87
DARPA Grand Challenge	Stanley	0.90	0.30	0.95	71.57

The NAVLAB UGV has significant dependence on the HI* as the operator must actuate the brake and throttle while the automated navigation functions provide the situational awareness and navigation functions against a 'flight plan.' If the human operator becomes distracted then the 'autonomous system' suffers significant performance loss and may not complete the mission successfully (SA<1).

Although the ARGO UGV provides the operator situational awareness and alerts to unsafe conditions, SRI noted that the mission complexity (MC) and environmental difficulty (ED) assessments were rated moderate to low. This indicates that the ARGO UGV may not have sufficient functionality or system autonomy to accommodate the expected traffic situations a normal driver would need to deal with. To improve the autonomous capability of the ARGO may require significant design changes or major re-designs and costs.

The CMU Houston-Metro Automated Bus operates in a very limited constrained environment (EC=3) and not designed to 'coexist with normally piloted manned vehicles'(McWilliams *et al.*, 2007). It was not clear if the CMU BUS was a very limited demonstration of what capabilities could be implemented or if the design would be matured to coexist in the normal traffic. What is evident is that there are design trade-offs that need to be done characteristic of early design phases.

The NASA SPIRIT is an interesting UGV in that communications latencies are significant because of the geospatial separation between the human supervisors and the UGV. The speed at which the SPIRIT mission operations function is relatively slower than the other

UGVs in the SRI study. This does not imply that communications latency should not be considered for the other UGVs in the study. Significant capability shortfalls, the ability to coexist with normal traffic, require analyses of reaction times and would need to be part of any requirement/design trade studies, not adequately supported by current methodologies.

Summarizing, a “Level of Autonomy” label based system autonomy tool has very limited usefulness in defining and developing system concepts. Label assessment tools do not provide visibility into system components or design contributors. Label assessment tools do not support parametric sensitivity or stochastic analyses. An algorithmic assessment tool can support design activities in developing system concepts.

5. Application of ASRF

The current global climate change situation provides such an application[4]. Retreating polar ice caps allow easier access to natural resources. Arctic bordering nations have filed perditions for claiming Arctic territory, Figure 10: Arctic Territorial Claims. Currently there are several international bodies that provide oversight to polar territorial claims and, as is often the case, coordination between competing international bodies provides confusion rather than clarity(ISTED, 2009).

The receding polar ice cap allows access to navigable waterways and resources. Recognized territorial claims establish ownership to significant and untapped oil and gas reserves. Ocean bottom and water column survey need to be performed to establish continental shelf territories and support claims of eminent domain and sovereignty. Significant polar ice coverage still exists, necessitating unmanned systems to perform surveys.

For navigation and transit under the Arctic ice cap, a system incorporating UUVs is needed to conduct the site survey. For this example scenario, a large displacement UUV would transit to the survey area to deploy multiple and smaller displacement UUVs.

Figure 10: Arctic Territorial Claims

<Figure head> Fig. 1: Arctic Territorial Claims

5.1. Notional Mission Scenario

In the AGILE/Rapid IT development methodology, USER STORIES (similar to CONOPS) are written to influence the functionality of the system being developed and provide the basis for defining the functions and requirements a system must include. While USER STORIES describe functionalities and capabilities, a USE CASE can be developed by combining and sequencing the needed functionalities and capabilities into a mission scenario.

The purpose of this scenario is to apply the principles of mission phase and mission time and illustrates utilisation of the assessment model in developing CONOPS and influencing AoA and other logistical life cycle information. This example scenario has multiple mission phases common to all candidate systems performing similar missions. Each phase describes a mission segment and duration needed. The first would be a launch phase from a home port, Φ1, requiring a duration of one half of a work day. The next mission phase would be a transit to the operation area, Φ2. When at the operation area, the sensors subsystems, small displacement UUVs, would be deployed and this would be identified as Φ3. The data collection from the survey would be described as Mission Phase Φ4. Upon completion of the survey, the small displacement UUV sensor subsystems need to be retrieved by the host large displacement UUV platform, Φ5. The host UUV would then perform a return transit to the home port, Φ6. Recovery of the host UV at the home

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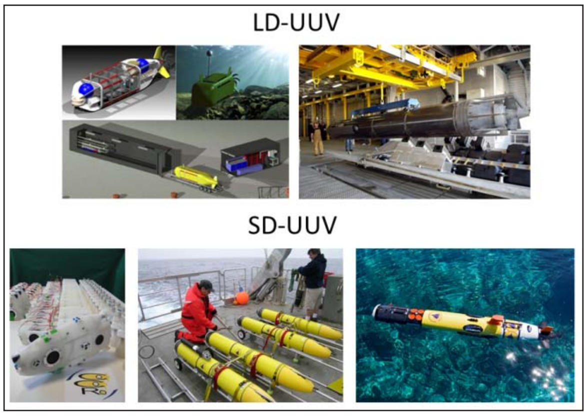
[4] The anticipated warming of the Arctic Oceans opens up economic opportunities and sovereignty issues as reported in the article Arctic Body Comes In From the Cold by Alistar MacDonald and Ellen Emmerentze Jervell, in the Wall Street Journal dated 13 May 2013.

port would be the final segment of this mission scenario, Φ7. This sequence of phases is similar to that shown in Figure 9 – Mission Phase.

Figure 11: Candidate UUVs



Time, as a variable, becomes a consideration in several ways. Complex mission scenarios may require several changes of system autonomy levels due to the changing phases of the mission like transit and area surveillance. This causes the SA vector, section 1), to have a Mission Phase dependency. The combination of human supervision/interaction and the level of needed machine automation may need to vary within each discrete mission phase. This causes the SA Vector to have a time variant or mission context dependency. Each Mission Phase has a duration and mission sequence similar to those shown in Figure 9.

5.2. Candidate Solutions

The development of requirements, Analysis of Alternative (AoA), Concept of Operation (CONOPS), Life Cycle Support Analysis are among the major activities during the very early design phases. A critical activity during the early design stage is the comparative assessment of candidate configurations. Those configuration would most likely be complex SoS. An autonomous systems assessment methodology that allows the relative comparison of human interaction-machine automation between candidate system concepts is needed to support those engineering design activities. Figure 11 identifies several potential candidate UUV that could be configured in SoS and their mission effectiveness assessed. The USN has several CONOPS and program to support arctic missions (Kaminski, 2012; Deyst & Egan, 2005; Hogg, 2009; Murphy & Shields, 2012; O'Rourke, 2006). A common thread is the use of large diameter UUVs (LD-UUV) for transit and smaller diameter UUV (SD-UUV) to perform ISR functions. The various UUV SoS configurations require various levels of human operator involvement. The ASRF tool box would be able to provide this rapidly needed assessment while the "Level of Automation' methods would be less productive in the AGILE environment.

6. Summary and Conclusions

Autonomous systems result from a complex integration of human intelligence supervising machine automation to adapt to unforeseen events encountered during operations Although significant work has been undertaken, conventional SA assessment frameworks are not suited for trade studies in support of AoA, CONOPS and requirements development. Missions are becoming more complex and require ever-increasing capabilities to adapt to varying unknown situations. Autonomy is a complex function of many dynamic and widely varying parameters and requires a mathematical relationship between Human Interaction and Machine Automation to provide the design tradeoff study capabilities needed during early development phases. The Defense Science Board stated that machine automation and human interaction assessments need algorithmic solutions instead of the label methodology. The mathematical relationship described in this paper provides a basis for such a framework. Incremental and partial capabilities models can be developed using rapid design methodologies.

Future development of System Autonomy Assessment tools would provide additional capabilities and mature the requirements refinement process for the development of autonomous systems currently not available.

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