Unmanned Vehicle Situation Awareness: A Path Forward

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ABSTRACT

This paper presents the concept of unmanned vehicle situation awareness and provides a discussion of how an unmanned vehicle situation awareness architecture can be developed based upon human situation awareness. A broadly adapted human situation awareness definition is directly applied to the notion of unmanned vehicle situation awareness. The paper also discusses unique unmanned vehicle aspects that will influence unmanned vehicle situation awareness. A preliminary formalization of unmanned vehicle situation awareness and the implications for human-unmanned vehicle interaction are provided.

INTRODUCTION

Many of today's deployed unmanned vehicle (UV) systems are teleoperated, semi-autonomous or rely on very fragile autonomous capabilities. Consequently, mission success requires the human to be a tightly integrated system component. The demands placed on human operators include requiring multiple personnel to support a single UV and cognitively demanding tasks associated with UV missions. Future UV systems will deploy individual or teams of fully autonomous UVs (The 2005 Joint Robotics Program Master Plan 2005; The Navy Unmanned Undersea Vehicle Master Plan 2004; Quadrennial Defense Review Report 2006; The Unmanned Aircraft Systems Roadmap 2005). These UV systems will likely incorporate humans in roles such as supervisors, operators, mechanics, peers, or bystanders (Scholtz, Antonishek and Young 2005). Such UV systems will require the UV to be capable of accurately perceiving the environment, understanding the situation, locating and interacting with environmental elements, and communicating mission assessments to team members or superiors (either human or machine).

Humans are able to understand highly dynamic and complex environments via their cognitive capabilities. One component of these cognitive capabilities is situation awareness (SA) (Endsley 1988; Endsley 1995a) namely, the human's ability to perceive the environment, comprehend the situation, project that comprehension into the near future, and determine the best action to execute. Thus far SA research, including UV SA research, has focused solely on the human's ability to attain and maintain SA. Our hypothesis is that a UV with human-like SA capabilities will improve the mission success of future UV systems while influencing and supporting the human's SA and interaction with the UV; resulting in a single human simultaneously supervising a larger number of vehicles.

The purpose of this paper is to present an initial formulization and definition of UV SA. This definition is based upon existing research in human factors that has focused on understanding situation awareness and the effect of increased system autonomy.

HUMAN SITUATION AWARENESS

Many definitions of human SA exist (Dominguez 1994; Endsley 1988; Endsley 1995a; Franker 1988; Sarter and Woods 1991). However, Endsley's definition is a commonly accepted definition that has been adopted in our work:

> "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley 1988).

This definition incorporates three levels of SA: level one - the perception of information from the environment; level two - the comprehension of the perceived information; and level three - the projection of the information into the near future for the purpose of guiding actions.

Figure 1 represents Wickens et al.'s model of human information processing (Wickens, Lee, Liu, and Gordon Becker 2004) with an overlay correlating the three levels of SA to the information processing model. Human information processing requires the human to simultaneously register sensory information, perceive the information based upon the sensory input and memory, allocate attentional resources, make decisions, select the appropriate action, and execute the selected action.

Recently there has been a focus on the human's SA for UV systems (Drury, Scholtz and Yanco 2003; Drury, Riek and Rackliffe 2006a; Drury, Yanco, Howell, Minten and Casper 2006b; Kaber, Onal and Endsley 2000; Yanco and Drury 2004). Most current UV systems require high-levels of human interaction and control. Often the UV resides at a remote location, thus limiting the human's understanding of the UV, the environment, and the UV's affect on the environment. One difficulty is limited or inaccurate UV sensing capabilities, particularly when compared to humans' rich sensing capabilities. Couple these factors with the fact that these sensors tend to provide output that is often presented in a human unfriendly format; thus placing a high cognitive demand on the human.

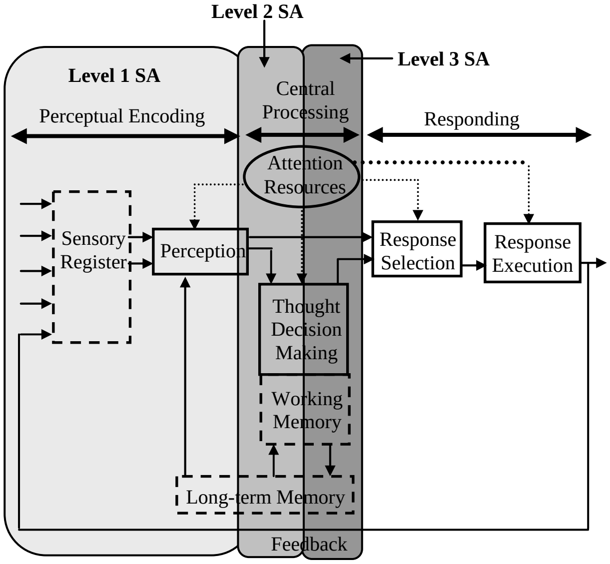

Figure 1. Endsley's SA levels overlaid onto Wickens et al.'s (2004) model of information processing.

A body of SA research focuses on human teams during interaction with one another and systems (Artman 2000; Artman and Garbis 1998; Endsley 1995a; Gutwin and Greenberg 2004; Salas, Prince, Baker and Shrestha 1995; Sarter and Woods 2000). Salas et al. (Salas, Dickinson, Converse and Tannenbaum 1992) defined a team as:

> "a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership."

Endsley (1995a) incorporates Salas et al.'s definition into her definition of team SA:

> "the degree to which every team member possess the SA required for his or her responsibilities."

The SA of all team members is required to ensure the success of the overall team. While individual team member SA is important, it is equally important to ensure that there is sufficient shared SA as needed for the task. Endsley and Jones (2001) defined shared SA as:

> "the degree to which the team members have the same SA on the shared SA requirements."

SA for an individual human is difficult to quantify; however team SA is far more complex to quantify. Both play an important role in defining UV SA.

Human SA is a very complex notion that is influenced by a number of internal and external factors (Endsley 1995b; Salmon, Stanton, Walker and Green 2006; Wickens 2002) and UV SA is just as complex. There exist many parallels between human SA and UV SA; however a one-to-one mapping does not exist. The existing literature related to human SA will shape the development of the UV SA architecture including the underlying architecture mechanisms, UV SA evaluation criteria, and the associated measurement and evaluation techniques. Many existing technologies associated with artificial intelligence and perception can contribute to UV SA; however they are individually insufficient for providing a UV with human-like SA. It is well known that SA has a significant effect on humans' abilities to successfully complete missions; thus future UV systems must provide similar capabilities. Known limitations with human SA may not be limitations with UV SA; however there may be newly identified limitations for UV SA that must be resolved.

UNMANNED VEHICLE SITUATION AWARENESS

Endsley's definition of SA was selected as the base definition for this work for a number of reasons. First, it is a commonly accepted human SA definition. Second, unlike other definitions, this definition is not human specific and can be applied to the UV SA architecture. Third, the definition maps nicely to Wickens et al.'s human information processing model (Wickens et al. 2004) that can be extrapolated for UV information processing. Finally, if the goal is to attain human-like SA and to support the human components of the UV system, then Endsley's definition is a very nice basis for defining UV SA. In fact, the definition can be employed word for word when discussing either human or UV SA. The differences appear when one develops a formal UV SA architecture.

This work was motivated by a number of factors. First, the development of fully autonomous UVs with SA requires a holistic development approach, rather than stove pipe technology development. Thus far, stove pipe development of artificial intelligence and autonomy has not provided the integration required to attain UV SA. Second, the development of fully autonomous UVs with human like reactive capabilities requires UVs to possess SA. Third, in order to improve human SA when working with remote systems, UV SA is required as user interaction capabilities and intelligent autonomous behaviors will not wholly resolve the issue. Fourth, in order to reduce the human-to-UV ratio, the number of UVs a single human can supervise simultaneously, UV SA is required. Current approaches that attempt to improve user interaction, intelligence, and/or autonomous behaviors will not solely lead to improved human SA or a reduced human-to-UV ratio. Finally, a number of UV SA levels will exist, similar in concept to levels of autonomy.

Human SA and UV SA

Human SA focuses on the human's ability to perceive the environment, comprehend the information that has been perceived, and project that information into the near future in order to select an appropriate response. SA in this context typically is defined in relation to a particular mission that must be attained over time; therefore knowledge of the associated mission goals and objectives determine the information required by the human to successfully complete the mission (Endsley, Bolté and Jones 2003). While the specific information requirements vary across domains, the common factor is that SA drives the humans' decision-making and performance.

Level One SA - Perception: Level one SA represents the perception of the environment relative to the assigned mission, including the environmental status, attributes, and dynamics. Humans rely on their visual, auditory, tactile, taste, and olfactory senses for environmental perception. Various combinations of sensor capabilities are necessary to perceive the relevant environmental aspects that vary across application domains.

Today's UV are not necessarily capable of perceiving the necessary environmental percepts. Many current UVs would ignore a relevant percept because they are programmed to focus on a particular environmental aspect and ignore others. Some perceptual limitations are known, such as the inability to see through walls or the automatic detection of environmental elements that may indicate an improvised explosive device (IED) and new sensor capabilities are under development to support such limitations. However, there are likely to be additional information requirements that humans take for granted, are not integral to human perception, or can be perceived by humans that unreliable hardware/software sensor capabilities cannot support. Future UVs must perceive all necessary information requirements in order to attain human-equivalent SA. The characterization of the military theater and future missions will be necessary to fully understand future UV perceptual sensor requirements and the characteristics of level one SA.

UVs do have a potential advantage over humans with regard to perception. First, UVs can provide dedicated vigilance for monitoring tasks that humans find dull and boring (e.g. persistent surveillance). Second, future UVs may have the capability to store all perceived information throughout the entire mission; therefore UVs may have flawless memory recall, unlike their human counterparts. Finally, future UV sensor technology may surpass human sensory limitations (e.g. night vision, auditory perception outside the human perceptual range).

UV SA for level one shares a number of similarities with human level one SA. First, it must represent a suite of sensing capabilities along with the sensor feedback, update rates, information resolution levels, and sensor fusion. Communications from other UVs or humans must also feed into the SA processing as they also represent percepts. UV SA must also incorporate the capacity for UVs to provide adaptive sensing, a capability that is significantly lacking today. Adaptive sensing incorporates the ability to determine which sensor to use at a particular time, modification of the sensor processing, or combination of sensors required based upon the task. Additionally, the SA architecture must provide the capability for the sensors to direct attention. These aspects must be integrated into the characterization of level one UV SA.

Level Two SA – Comprehension: Humans achieve level two SA by integrating their environmental perceptions (level one SA) with their goals and associated information from memory. Similar capabilities will be required in order to achieve human-like UV SA. Level two SA requires that the UV integrate the large amounts of perceived data and prioritize the importance and meaning of the integrated information with regard to mission goals. Current UVs either rely on the human operator to understand the situation or blindly carryout the assigned mission. Existing UVs that incorporate intelligence capabilities do not necessarily possess situational comprehension (e.g. artificial intelligence $\neq$ comprehension).

It has been shown that level two SA can be improved in humans by providing additional training and experience that results in a mental model of the task, thus improving the humans' ability to understand the task and appropriately integrate the information. A human limitation is that individuals new to a situation cannot easily acquire the mental models of those who have previously experienced the domain. Therefore, their performance levels are typically lower than those of individuals with more experience. One aspect that requires characterization for level two UV SA is the transfer of comprehension capabilities between unmanned entities, thus eliminating or reducing the novice user phenomena observed with humans.

Level two UV SA will account for UV comprehension of the percepts based upon components that effect human comprehension. These include: expectations (which may be a side-effect of human programming), mental models, working memory, long-term memory, redirecting attentional focus, prior decisions, and prior plans. Some of these components have been individually developed but are not integrated into a holistic architecture that will lead to an UV achieving level two SA.

Level Three SA – Projection: Humans are able to predict what will occur in the near future based upon their perception and comprehension of the situation, thus level three SA is directly dependent upon attaining good level one and two SA. Projection requires an excellent understanding of the mission domain (e.g. mental model) and is frequently a highly demanding cognitive activity. Various aspects such as cognitive workload, mental capacity, and environmental stressors can limit humans' level three SA.

Current UV technologies, such as mission planners and decision support systems, have a limited ability to emulate human projection. UV level three SA will incorporate working-memory, long-term memory, decision making, mental models, and expectations. Further analysis of human SA may indicate additional aspects to be integrated into UV SA.

The entire UV SA architecture must provide connections between the levels as perceptions (level one) are required for comprehension (level two) and both of these lower levels feed into projecting the actions to perform (level three). A holistic, system-of-systems approach is required to integrate existing stove pipe capabilities developed across the field with novel elements into an UV SA architecture.

General Human SA Characteristics: Many factors effect human SA across the three levels. Time is one such characteristic. Humans often rely on timing to direct their perception, comprehension, and projection based upon specific events or mission characteristics. Dynamic environments frequently affect the temporal component of SA. SA is highly dynamic, changes quickly, and can become outdated or inaccurate.

Human perception is limited and finite; however UVs may provide the capability to surpass such limitations. Humans typically manage their attentional focus based upon the frequency that percepts must be updated or the information update rate. Future UVs will suffer from similar limitations; however the saturation point for information collection will be higher than for humans. Human perception is also limited by the human's ability to parallel process sensor percepts due to sensor modalities and working memory constraints. UVs may encounter similar situations and must be able to manage attention or the processing of percepts; the UV SA architecture will need to direct attention and percept processing appropriately. Current UV technology does not necessarily consider these aspects of perception; particularly how they affect awareness.

Humans possess working (short-term) memory and long-term memory. Short-term memory suffers from limited capacity and humans have unreliable long-term memory recall. At the simplest level, the UV's random access memory could be employed as working memory while a hard drive can be employed as long-term memory. However, the UV's memory constructs may need to more accurately emulate the human's cognitive constructs. Phillips and Noelle (2006) have developed a preliminary artificial working memory model for a humanoid robot. This and other work related to developing working memory will provide insight to the characterization of UV SA.

Due to the limitations associated with human memory, humans tend to rely upon mental models, schemas, scripts, and heuristics. A mental model represents how something works, while a script provides a sequence of actions relevant to a particular situation. Finally, heuristics allow humans to react with a fairly good probability of success based upon their prior experience. Humans tend to generalize existing mental models, schemas, scripts, and heuristics to unknown or similar situations often resulting in less than optimal performance (Wickens et al. 2004). Constructs such as schemas and mental models have a clear contribution to the UV SA architecture that will serve to make the UV SA more efficient. UVs may have the capacity to rely less on heuristics than their human counterparts, thus increasing the likelihood that the UV will provide a high probability of mission success. This premise is based on the notion that UVs will be able to process larger amounts of information without the limitations associated with human cognitive processing, thus providing accurate and optimal performance.

Humans frequently rely on predetermined expectations to guide their perceptual attention, comprehension, and projection. Expectations can reduce the amount of information required to comprehend a situation and project future actions, thus reducing the human's cognitive workload. However, inaccurate expectations also lead to misunderstandings and inaccurate projections. UVs do not typically possess expectations in the same manner as humans; however such a construct may be a necessary component in the SA architecture. One concern would be the introduction of human expectation biases by the UV designers and developers.

Figure 1 represents the human information processing model and the associated SA levels. The UV specific information processing model removes the human's working and long-term memory representations and replaces them with the notion of an UV memory construct. Many of today's UVs rely on a world model; however there are many limitations associated with world models that will have to be overcome in order to provide human-equivalent SA. It is possible that the SA architecture will require the representation of a multiple level memory, perhaps similar to the human's working and long-term memory structures. Note, that at this time, it appears that the other components of the information processing model appear to map directly to the same model for UVs. Additionally, the overlay of Endsley's three levels of SA remains unchanged for the UV information processing model. In fact, Endsley's definition (Endsley 1988; Endsley 1995a) of human SA can be adopted directly for the UV SA architecture.

A broad spectrum of research exists that characterizes human SA including human team SA. The above represents a selection of human SA characteristics that are to be evaluated in order to extract appropriate elements for UV SA. Additional human SA characteristics include stress, training, capabilities, human error, communication errors, and task complexity. A review of the individual and human team SA research will provide a preliminary characterization for the UV SA architecture.

Automation Level and SA

Human SA is highly sensitive and can be affected by any number of external (e.g. environmental stressors, salience, automation) or internal (e.g. cognitive workload, vigilance, fatigue, stress) factors. Automation was originally touted as a mechanism to reduce the cognitive demands placed on humans; however it has been demonstrated that SA can be reduced as the level of system automation increases (Parasuraman, Sheridan and Wickens 2000; Sarter and Woods 2000; Wickens 2002).

A current working assumption is that the level of required UV SA correlates to the UV's level of autonomy. Parasuraman et al. (2000) revised Sheridan and Verplank's (1978) ten levels of autonomy. Similarly, Endsley and Kaber (1999) and the Army scale for the Future Combat System (NRC 2005) each provide ten slightly different levels of autonomy. Irrespective of the definitional differences, at the lowest autonomy level the human has full control of the UV and the UV has no autonomy, thus the UV may have little, if any SA (today the UV has no SA or very limited level one SA). A fully autonomous UV will require human-like SA capabilities to ensure safe and successful mission completion. The intermediary levels of automation will result in varying relationships between the human and the UV, thus resulting in varying the levels of SA for each entity. A proper UV SA architecture must delineate the characteristics required for varying levels of autonomy in addition to how the level of UV SA influences human SA.

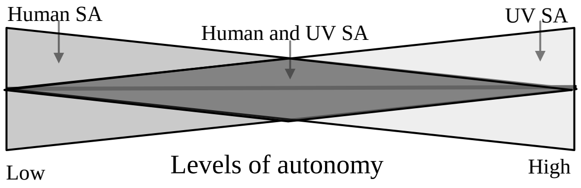

Figure 2. An allocation of human and UV SA across the levels of autonomy.

Figure 2 provides a potential representation of the levels of UV SA as the level of autonomy spans from full human control to fully autonomous unmanned capabilities. At the lowest autonomy level, the human possesses the SA required for mission success, while at the highest level the system possesses the required SA. As the level of autonomy transitions from low to high, the UV will increase its level of SA while the human's level of SA decreases. This preliminary representation indicates that the lowest level of autonomy is similar to current systems, where the onus for possessing SA is placed on the human. However, it may be important for the UV to possess some SA in order to improve the human's SA. Additionally, at the highest level of autonomy, the human may not require a high SA level throughout the entire mission; but there may exist situations during which the human must possess a high SA level.

There are a number of factors that require further analysis that could dramatically change the representation presented in Figure 2. How the amount of SA that each entity requires changes and how does that change effect mission performance? Given this information, is there a level of autonomy at which the human and UV equally share SA? Future UVs will likely employ adjustable autonomy where the autonomy level changes based upon the situation; therefore how will adjustable autonomy affect the UV SA architecture characteristics and how will known issues with human SA associated with high levels of autonomy be avoided? Finally, should a teleoperated (full human control) system possess some level of SA? These types of questions represent some of our current work in developing the UV SA architecture; however this does not hinder our ability to develop a preliminary formulization of UV SA.

Formalized UV SA

Existing knowledge of individual human (SA_H) and human team (SA_{HT}) SA can be employed to develop a preliminary representation of UV SA. SA_H typically focuses on a single human interacting with a system and is commonly improved by providing better interfaces between the human and machine. Human SA does not represent the machine's ability to possess SA. It is therefore necessary to develop a new formalization that represents each entity's contribution to SA. It is not currently clear if this new formalization is identical to the constructs that represent human team SA; therefore we currently delineate system SA (SA_S) and system team SA (SA_{ST}).

System SA at the simplest level represents a single human, SA_H, interacting with a single vehicle, SA_V, and the combination represents the system SA, SA_S. Formally, the union of the SA from each entity provides the system SA:

$$SA_S = SA_H \cup SA_V \quad (1)$$

where the individual SA_H and SA_V contributions vary based upon the UV's level of automation. When SA_V is the empty set, then SA_S is simply SA_H. However, when neither set is empty, Equation 1 represents each entity's contribution to the UV system SA based upon the level of autonomy, perhaps as shown in Figure 2.

The level of UV automation will influence SA_V; however there are a number of other characteristics that will determine SA_V. Formally, SA_V can be represented as:

$$SA_V = (Level\ of\ autonomy \times C) \cup E \cup X$$

where (*Level of autonomy* x *C)* represents the characteristics specifically associated with the autonomy level, *Envir* represents the characteristics that are environmental in nature, and *X* represents the characteristics that are unrelated to the level of autonomy or the environment. One focus of characterizing SA_V requires the delineation of the elements that comprise sets *C*, *Envir*, and *X*. Set *C* may incorporate a number of factors including workload, stress, attention, perception, memory, and vigilance. Weather, terrain, location, and operational requirements represent a few of the items to be included in the *Envir* characteristic set, while the set of other characteristics (*X*) may include items such as training, capabilities, task complexity, and communication errors. While these characteristics in general are shared across humans and UVs; the exact meaning, representation, and implications will differ and requires appropriate representation in the UV SA architecture.

Unmanned entities with a middle level of autonomy will result in an intertwined relationship between the human and unmanned vehicle, such as the unmanned entity and the human acting as peers. Human team SA delineates between team SA and shared SA where shared SA represents the SA that all team members' share. Given Equation 1 that indicates that both the unmanned entity and the human will contribute to system SA and the level of autonomy, resulting in a shared relationship, it is necessary to define shared system SA, $SA_{Sshared}$. Essentially, $SA_{Sshared}$ is the intersection of the SA elements that both entities possess specific to the shared activities:

$$SA_{S_{shared}} = SA_H \cap SA_V\ . \quad (2)$$

SA_S and $SA_{Sshared}$ may be sufficient for representing a UV system in which there is a single human interacting with a single UV; however it does not appear to accurately represent UV systems in which there are teams of humans, teams of UVs, or a combination of the two. Equations 1 and 2 must be extended to account for future UV systems that team UVs with other UVs and/or humans. The system SA (SA_S) represented by Equation 1 can be extended to represent system level team SA (SA_{ST}) as follows:

$$SA_{ST} = SA_{HT} \cup SA_{VT} \quad (3)$$

where the SA of the human team (SA_{HT}) is:

$$SA_{HT} = \bigcup_{1}^{i} SA_{H_i}$$

and the UV team SA (SA_{VT}) is:

$$SA_{VT} = \bigcup_{1}^{j} SA_{V_j}\ .$$

Equation 3 provides a representation of the system level SA for teams; however it does not account for the shared SA commonly found in human team environments or the shared SA represented by

Equation 2. The shared SA represented by Equation 2, when extrapolated to teams, represents the smallest set of SA shared by all team members and is represented as:

$$SA_{ST_{shared}} = SA_{HT_{shared}} \bigcap SA_{VT_{shared}} \quad (4)$$

where $SA_{HTshared}$ is:

$$SA_{HT_{shared}} = \bigcap_{1}^{i} SA_{H_i}$$

and $SA_{VTshared}$ is:

$$SA_{VT_{shared}} = \bigcap_{1}^{j} SA_{V_j} \; .$$

Equations 3 and 4 represent a situation where all entities are working as a team; however it is possible that this representation requires further delineation to incorporate teams comprised of multiple sub-teams. For example, a team comprised of three sub-teams will have individual sub-team SA that will feed into the overall team SA, SA_{ST}. Similarly, each sub-team will have a shared SA; this shared sub-team SA will differ from the overall team shared SA, $SA_{STshared}$. Future UVs will incorporate a combination of humans and UV entities into a single team. Understanding the additional dimensions of human team SA will be necessary to fully characterize and develop the UV SA architecture.

This preliminary UV SA representation is intended to provide an understanding of the interconnections between humans and UVs based on the existing definitions of human SA, team SA, and shared SA. These interconnections and the delineation of UV SA characteristics are driving the development of the UV SA architecture.

CONCLUSIONS AND FUTURE WORK

This paper presents the concept of unmanned vehicle (UV) situation awareness (SA) and provides a preliminary discussion of how UV SA can be defined based upon human SA. Endsley's (1988; 1995a) commonly accepted SA definition has been directly applied to the notion of UV SA; however it is also necessary to develop a formalization specific for UV SA. This paper discussed some of the similarities, considerations, and differences with human SA that must be accounted for when formalizing UV SA. This includes the level of automation that the UV system possesses; the role of humans when interacting with the UV system; and the number of humans and UVs present in the system (e.g. individuals vs. teams). The result is the presentation of a preliminary formalization of the UV SA architecture.

The formulation of UV SA is in the preliminary stages and further work is required in order to fully formulize the architecture. The work reported here is based upon a preliminary review of the aspects that characterize human SA and we are currently conducting a more formal review. We are also conducting a review of existing fully autonomous systems, both within and outside of the unmanned vehicles domain, to identify specific characteristics that must be included in the UV SA architecture. We are also collecting characteristics based upon a review of systems across the levels of autonomy. Once we have fully characterized UV SA, we will develop evaluation criteria and associated measurement tools for assessing UV SA.

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