A Decomposition of UAV-Related Situation Awareness

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ABSTRACT

This paper presents a fine-grained decomposition of situation awareness (SA) as it pertains to the use of unmanned aerial vehicles (UAVs), and uses this decomposition to understand the types of SA attained by operators of the Desert Hawk UAV. Since UAVs are airborne robots, we adapt a definition previously developed for human-robot awareness after learning about the SA needs of operators through observations and interviews. We describe the applicability of UAV-related SA for people in three roles: UAV operators, air traffic controllers, and pilots of manned aircraft in the vicinity of UAVs. Using our decomposition, UAV interaction designers can specify SA needs and analysts can evaluate a UAV interface's SA support with greater precision and specificity than can be attained using other SA definitions.

Categories and Subject Descriptors
D.2.2 [**Software**]: Design tools and techniques: user interfaces.

General Terms
Design, Human Factors, Verification.

Keywords
Situation awareness, unmanned aerial vehicles (UAVs), user interaction requirements, interaction design, evaluation.

1. INTRODUCTION AND RELATED LITERATURE

Situation Awareness (SA) is an interesting and well-researched concept. There have been many definitions proposed for "awareness" (see Drury et al. 2003 for a long list culled from the literature), but the most widely-accepted definition of SA was suggested by Endsley (1988) as follows: [Level 1] the perception of the elements in the environment within a volume of time and space, [Level 2] the comprehension of their meaning, and [Level 3] the projection of their status in the near future.

Endsley has done significant work in the air traffic control domain, and her SA definition arose out of that work. The SA definition assumes that the human is the only intelligent entity in the system that needs information on the other parts of the system. When humans work with robotic systems, however, the robots need information about the environment and (if applicable) other robots in the team, as well as relevant instructions from humans. Further, Endsley's air traffic controllers primarily sit in one room; thus her definition does not address awareness of distributed team members' activities, except if one thinks of other people as being "elements in the environment."

In fact, people are not normally thought of as simply being another "element in the environment." This phrase is very broad: in the context of teams of people working with multiple UAVs, it must be stretched to encompass awareness of where each UAV and each team member is located and what they are all doing at each moment, plus all the environmental factors that affect operations such as their proximity to each other and other objects/people. While this breadth may be useful in many applications, we found that it was not helpful when trying to measure SA of UAV operators.

There is a rich literature in measuring SA[1]. However, there is a wide divergence of opinion on what, exactly, should be measured: how much attention is required (Taylor, 1990; Vidulich et al., 1991)? Can people answer random questions correctly about the environment when interrupted in their tasks (Endsley, 1988; Endsley et al., 1998; Durso et al., 1995)? Is the task outcome correct, thus implying that people performing those tasks must have had good SA (Brickman et al., 1999)? In our previous work on the human-robot interaction (HRI) of urban search and rescue robots (Yanco and Drury, 2004), we used a combination of techniques to capture different facets of a robot operator's understanding of the situation, especially since an operator may have more awareness about some aspects of the environment and less awareness about others. To better characterize SA, however, we needed a way to describe which aspects of SA were attained by robot operators, and which aspects were lacking.

Accordingly, as part of our earlier work we developed a definition of HRI awareness that takes into account the asymmetric, two-way nature of the awareness relationship, as well as the fact that teams of people may be working with teams of robots, all of who may need different types of information about the others (Drury et al. 2003). It also provides more specificity than that afforded by Endsley's definition. The five components of this definition can be found in Table 1.

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[1] See, for example: Brickman et al., 1999; Durso et al., 1995; Endsley and Garland, 2000; Endsley, 1988; Endsley et al., 1998; Ericsson and Simon, 1980; Fracker, 1991; McGuinness, 1999; McGuinness and Ebbage, 2002; Scholtz et al., 2004; Taylor, 1990; and Vidulich et al., 1991.

Once we began working with UAVs, however, we found that neither the HRI awareness definition nor Endsley's definition fully captured the awareness needs pertaining to operators of airborne robots. Instead, a more detailed and fine-grained understanding of UAV-related awareness needs was required. For example, does an operator have "good" SA if they have an up-to-the-moment understanding of where the UAV is in relationship to the ground while not realizing that the UAV is on a collision course with another UAV? We feel it is helpful to be able to say that this operator has sufficient SA of the UAV's spatial relationship with respect to the terrain but has no SA with respect to other aircraft.

This paper describes our modifications to the HRI awareness definition to develop a decomposition of human-UAV awareness. Further, it ends with an example of applying this decomposition to an analysis of awareness deficiencies in the case where Air Force personnel were learning how to be operators of the Desert Hawk UAV.

Table 1. Human-Robot Interaction Awareness, General Case (Drury et al., 2003)

Component	**Definition**
Human-robot	The understanding that the humans have of the locations, identities, activities, status and surroundings of the robots. Further, the understanding of the certainty with which humans know the aforementioned information.
Human-human	The understanding that the humans have of the locations, identities and activities of their fellow human collaborators.
Robot-human	The knowledge that the robots have of the humans' commands necessary to direct their activities and any human-delineated constraints that may require a modified course of action or command noncompliance.
Robot-robot:	The knowledge that the robots have of the commands given to them, if any, by other robots, the tactical plans of the other robots, and the robot-to-robot coordination necessary to dynamically reallocate tasks among robots if necessary.
Humans' overall mission awareness	The humans' understanding of the overall goals of the joint human-robot activities and the moment-by-moment measurement of the progress obtained against the goals.

2. METHODOLOGY FOR DEVELOPING THE AWARENESS DECOMPOSITION

The human-robot interaction awareness definition in Table 1 has worked well with ground-based robots, but our work with UAVs has caused us to adapt that definition. While we wished to characterize an operator's SA with more specificity, we felt it would be counterproductive to tie an SA characterization to a specific interface instantiation. Rather, our intent was to describe what UAV operators need to be aware of in some detail, yet still have those SA components be generally applicable to UAV operations.

For example, our observations of UAV operators (described below) have led us to realize that we need to say more than the facts that humans need to understand the UAV's "surroundings" and "status." In particular, humans need to know about the weather around the UAV because thunderstorms or extremely high winds may force a change of course or immediate landing. Although weather could be construed to be part of a robot's surroundings, it is important enough to call out separately.

To understand human-UAV SA, we started with the base case: one human directing one UAV. We determined the components of this base case by observing people interacting with one UAV at a time in realistic situations using Boiney's ethnographic-based techniques (Boiney, 2005). These information gathering and analysis techniques were chosen because they were designed to yield insight into time-sensitive situations such as those that occur when operators of UAVs have only a handful of seconds to obtain SA prior to making decisions about how they should direct the aircraft. We observed where operators' attention was focused and what information cues they relied upon to make decisions regarding how they should direct the UAV and conduct their mission. We also interviewed UAV operators to ask them what type of information they needed when conducting missions. While most UAVs were directed by teams of operators, we concentrated on observing the interaction between each operator and the aircraft to determine the base case. Finally, we obtained four UAVs of our own and have flown them to better understand some of the awareness issues surfaced in our previous observations and interviews.

After defining the base case, we moved to the general case: *M* humans and *N* UAVs. To gain additional insight for the general case we observed teams of people directing one UAV and (since multi-UAV operations are rare in practice) we drew upon our previous experience of observing operators directing multiple ground-based robots. Further, we also launched two of our own UAVs simultaneously.

The resulting base and general cases are stated below.

3. HUMAN-UAV AWARENESS DECOMPOSITION: BASE CASE

Base case: Given one human and one UAV working together, human-UAV interaction awareness consists of the understanding that the human has of the UAV's:

3D spatial relationship between…

the UAV and points on the earth: The operator may need to understand how far the UAV is from its home base, for example, to estimate how much spare power (fuel or battery life) may be available for detours.

the UAV and other aircraft: The operator needs to know that other aircraft are in the vicinity, and how far away the other aircraft are from the UAV.

the UAV and terrain: The operator needs to understand where the UAV is with respect to mountains or other terrain.

the UAV and targets: In the case where the UAV operator is responsible for obtaining imagery of targets or destroying targets (which may be other vehicles as opposed to stationery points on the earth), the UAV operator must understand where the UAV is with respect to these targets.

Predicted 3D spatial relationships: The operator must understand where the UAV will be flying in the near future, and where it will be with respect to points on the earth, other aircraft, terrain and (if necessary) targets. This predictive knowledge is necessary if the operator is to have enough warning to take any corrective or evasive action that might be necessary.

Weather near the UAV: The operator needs to know about high winds that may affect UAV flight performance, inclement weather that may force a detour or an immediate landing, or anything that could result in obscured vision (especially when using daylight or electro-optic cameras) such as clouds, mist, fog, or rain.

Health of the UAV: The operator needs to know whether the state of the UAV's operating parameters indicates a malfunction or other deficiency so that he or she can take corrective action (to include the possibility of an immediate landing).

Status of the UAV: The operator needs to know the state of the UAV's operating parameters besides those related to health. For example, the operator of a Desert Hawk UAV needs to know what type of camera is being used, because the controls function differently based on the camera type.

Logic of the UAV: The operator needs to have a model in his/her mind based on the UAV's internal programming, so that he/she can predict the UAV's responses to various conditions. For example, a UAV may include fail-safe programming that involves a return to a "home base" if it loses communications with the ground station. Thus, if an operator sees that a UAV is off-course and cannot communicate with it, the operator may assume that the UAV will fly directly to home base.

UAV's mission: The operator needs to have an overall idea of the UAV's mission. For example, if the operator knows the UAV must maintain surveillance of a specific object or point on the earth, he or she can quickly verify proper mission performance by looking to see that the object is in view of the UAV's video camera.

UAV's progress towards completing the mission: The operator needs an understanding of how far along the UAV is in completing the mission. Continuing the example just cited, if the UAV operator cannot see the object to be surveilled, he/she needs to know if the UAV is en route to that object and its estimated time of arrival. If it is overflying the target, the operator needs to know how much longer the target needs to be kept in view.

Degree to which the UAV can be trusted: The operator needs to understand the probability that commands sent to the UAV will be correctly executed, and that the data sent back from the UAV is accurate.

Further, human-UAV interaction awareness consists of the knowledge that the UAV has of the:

Human's commands necessary to direct a UAV: The UAV needs to know where to fly (its course and altitude), what speed to fly at, which sensors and/or weapons to deploy (and when to deploy them), and the degree of autonomy with which to act. When multiple UAVs are present, each UAV needs to know how they should cooperate with the other UAVs (if at all).

Human-delineated constraints that may require a modified course of action or command noncompliance: The UAV needs to maintain knowledge of any pre-programmed fail-safe modes, such as "return to home base".

4. HUMAN-UAV AWARENESS DECOMPOSITION: GENERAL CASE

Similar to the assumptions used in the original HRI awareness definition, we assume that teams of people may be directing multiple UAVs simultaneously, and the UAVs may need to obtain information from each other in order to carry out their missions. We have defined a general case for human-UAV interaction awareness consisting of four parts, as follows.

Human-UAV Interaction Awareness general case: For each human *m* of all *M* humans, and for each UAV *n* of all *N* UAVs working together on a synchronous task, human-UAV interaction awareness consists of four parts:

Human-UAV: the understanding that *m* has of: *N*'s identities, current 3D spatial relationships between *N* and other objects (points on the earth, other aircraft, terrain, and targets, if applicable), predicted future 3D spatial relationships, weather near *N*, health of *N*, other (non-health-related) statuses of *N*, the logic used by *N* when acting on *M's* commands, *N*'s missions, their progress towards completing their missions, and the trust *m* has for each of these items.

Human-human: the understanding that *m* has of the locations, identities and activities of *M*.

UAV-human: the knowledge that *n* has of *M*'s commands necessary to direct their activities and any human-delineated constraints that may require a modified course of action or command noncompliance.

UAV-UAV: the knowledge that *n* has of: the commands given to it, if any, by *N*, the tactical plans of *N*, any exceptional health conditions present in *N*, any exceptional weather conditions present near *N*, and any other coordination necessary to dynamically reallocate tasks among *N* if needed.

Since the general case of the human-UAV interaction awareness decomposition assumes the possibility of multiple UAVs, complete human-UAV awareness means that the interface enables humans to understand the state of the state of each of the UAVs, such as their health (for example); and not just the state of one UAV.

Most of the adaptations from the original HRI definition concern the human-UAV awareness portion of the decomposition. These changes are necessary because of the 3D spatial environment of

UAVs rather than the (nominal) two-dimensional environment of ground-based robots and the extreme importance of weather and platform health. In fact, it could be argued that these characteristics may be very important to some ground-based robot situations, in which case the original definition should be amended to include these components. Note that the fifth part of the HRI awareness definition, humans' overall mission awareness, was folded into the human-UAV portion of the definition in the form of understanding the progress towards completing the mission.

5. ROLE-BASED DIFFERENCES

Scholtz (2003) cites five different types of roles in human-robot interaction: Supervisor, Operator, Teammate or Peer, Mechanic, and Bystander. The degree to which humans will need to know all the items included in the decomposition will be dictated by their role. People directly controlling the UAV, whether directing the flight controls or the sensor controls, are in the "operator" role; pilots of manned aircraft in the vicinity are "peers" to UAV operators, and air traffic controllers are in a "supervisory" role since they direct the activities of both pilots and UAV controllers. Of the three roles mentioned, the operators of the UAV ground control stations will obviously have the greatest need for awareness about the UAV, but the military and civil air traffic controllers responsible for directing UAVs in their airspaces and pilots of manned aircraft in the UAVs' vicinity also have awareness needs regarding UAVs.

Table 2 presents information regarding the applicability of each of the awareness components to people in three roles: UAV operation, air traffic control, and pilots of nearby manned aircraft. A check mark indicates complete applicability, and the word "partial" indicates that the awareness component is partially applicable to people in the specified role. Note that "partial" awareness of 3D spatial relationships and weather for pilots of manned aircraft would primarily pertain to situations in which collision or weather avoidance would result in a change in flight path. Health of the UAV would be relevant to air traffic controllers or pilots in cases in which the UAV is experiencing an emergency and needs to land immediately. Awareness of the UAV's mission and progress towards completing that mission would be needed when the dynamic nature of the mission would cause changes to the UAV's flight path.

Table 2 can be thought of as providing a set of SA requirements for humans in the different roles pertaining to UAVs. When existing interfaces do not provide sufficient awareness of the specified types, these awareness gaps can be used to make improvement recommendations. For example, an interface for UAV operators may facilitate excellent awareness of the health of UAVs but not the weather near the UAVs; the decomposition can be used to point out these gaps. Further, information may be provided in the interface yet the operator may not have a true awareness of this information because the interface was ineffective in conveying the understanding of the information to operators.

6. UTILITY

To evaluate the utility of the human-UAV awareness decomposition, we used it to analyze data we had previously collected from a Desert Hawk UAV training session.

Table 2. Awareness Decomposition Regarding UAVs in the Larger Aviation Community

Awareness component from Human-UAV Awareness	UAV Ops	ATC	Pilots*
UAV aircraft identities (which one is which)	✔	✔	✔
Current 3D spatial relationships between the UAVs and other objects (points on the earth, other aircraft, terrain, targets)	✔	✔	Partial
Predicted future 3D spatial relationships between the UAVs and other objects (points on the earth, other aircraft, terrain, targets)	✔	✔	Partial
Weather near the UAVs	✔	✔	Partial
Health of the UAVs	✔	Partial	Partial
Logic used by the UAVs	✔	Partial	Partial
UAVs' missions	✔	Partial	Partial
Progress towards completing the missions	✔	Partial	Partial
The trust the human has for the information provided for each of the above	✔	✔	✔

*specifically, pilots of inhabited aircraft

The Desert Hawk UAV (see Hehs (2003)) is a battery-operated, 7-lb, 4-foot wingspan aircraft, with on-board sensors. It is usually flown autonomously using waypoint navigation, but can be re-tasked in flight either by being provided new waypoints, or by human tele-operation. A laptop interface provides the means for issuing commands to the aircraft and viewing its mission status. A video monitor displays sensor output, and allows "pushpin" (snapshot) picture taking. Figure 1 depicts the aircraft.

Seven Air Force personnel were being trained to operate the Desert Hawk[2]. This 10-day training session provided us with ethnographic observation[3] data that consisted of interview transcripts and notes taken during their classroom sessions and training flights. Our primary purpose for data gathering was to better understand UAV operators' work flow, collaboration, and information needs prior to designing improved human interfaces for UAV control.

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[2] All students had a similar set of prior military training, and performed similar jobs duties. Four students had used a flight simulator; three students had played pilot-like video games. None of the students had ever flown a UAV or remote-controlled airplane prior to coming to the training. All students were comfortable using a computer.

[3] Ethnography is method for observing a small number of people in their context (environment), as a means to gain understanding of their circumstances. See Crabtree (2003) or Thomas (1995) for a more detailed description.

Figure 1. The Desert Hawk aircraft[4]

All training flights had one pilot, who supervised the mission, and one payload operator, who observed the sensor output. Students alternated between these two roles. While both types of UAV operators needed cognizance of all of the aforementioned awareness components, individuals in the pilot role were especially in need of awareness because they had primary responsibility for ensuring mission safety.

When we observed the Desert Hawk training flights, we focused on recording "breakdowns": occasions in which operators experienced difficulties trying to complete the mission. We had learned from previous experience evaluating user interfaces that breakdowns or other negative incidents can often quickly point to areas in which the user interaction design should be improved. For this analysis, we took the set of observed incidents in which the pilot experienced problems completing a mission and examined the incidents to determine whether the human-UAV awareness decomposition could be used to identify at least some of the causes for the pilots' difficulties.

Table 3 contains a brief description of the incidents and a mapping of the incidents to the type of human-UAV awareness component(s) that were either lacking entirely or were insufficient. The table's columns are: Incident Number (non-ordinal, simply for reference), Incident Type (the kind of difficulty that was experienced), Description (of the incident), and SA Component (the type of awareness that was lacking or insufficient). For each incident (aside from #6) there was one pilot, *m*, and one UAV, *n*. For general problems that all operators had, *M* is used.

The first three incidents listed in Table 3 pertained to weather. If pilots had better awareness of the wind speed, in particular, he or she might have been able to compensate and avoid the crashes. (The light weight of this foam aircraft makes it particularly sensitive to high winds.) For incident #1, it was unclear to the student how the aircraft was going to respond in the face of strong winds; additional awareness of the aircraft's logic in this situation would have enabled the pilot to better predict the aircraft's future actions. Similarly, the pilot was not aware of how the aircraft's autopilot logic would handle the situation of a stuck control surface (incident #4). Accordingly, the pilot didn't know whether the logic could be trusted to compensate for, or potentially rectify, the control surface problem. A final example in which the pilot would have benefited from knowing more about the aircraft's logic can be seen in incident #5, which concerned the aircraft continuing an orbit pattern erroneously. The student was also not sufficiently aware of the mission's progress (or lack thereof) when the aircraft failed to fly to the final pre-programmed waypoints.

In incident #6, two sets of students were flying simultaneously at night using two aircraft and two ground stations. Since the aircraft interface was designed for displaying information about one aircraft at a time (the one under direct control), the students did not have enough awareness of what the other pair was doing, nor did they know how close together their aircraft were or how soon the other aircraft was going to land (and where). To compensate for this lack of information provided by the interface, they loudly verbalized questions and ran back and forth between the two operator control station setups.

Incidents #7 - #10 each pertained to insufficient awareness of the aircraft's spatial relationships. Incidents #7 and #8 concerned a lack of awareness of the aircraft's landing and launch points. In incident #9, there was insufficient information in the interface to provide the pilot with the awareness of the type of sensor in current use. Since the effects of the controls were reversed with one of the sensor types due to the use of a mirror, the pilot had difficulty operating the controls in the correct direction. As a result, the pilot was not able to predict correctly future spatial relationships based on taking individual control actions. Incident #10 was due to differences in status values reported by two different displays. Pilots were unsure of the aircraft's correct spatial relationships, health, and mission progress as a result.

7. DISCUSSION

In each incident described above, the pilot would have been aided, to varying degrees, by having additional awareness information. Not all of the problems would have been prevented if the interface had provided additional awareness information, but the lack of certain types of information was unhelpful at best. The use of the human-UAV awareness decomposition enabled us to specify the types of awareness information that were missing or insufficient in each case. As a result, this analysis supported our recommendation that weather information (at least wind speed) and a better depiction of spatial relationships be included in an improved interface design.

While we were able to use the awareness decomposition to analyze incidents gathered through observation, the approach we used for this particular analysis is not the only one possible. We can envision a more thorough data-gathering approach that involves periodically sampling the pilot's SA throughout the entire duration of a flight at pre-determined intervals. For example, an experimenter might use a chart containing time

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[4] Photo source: Air Force Link Media Center Photo Archive, http://www.af.mil/media/photodb/web/050204-F-0000P-15.jpg

Table 3. Awareness Decomposition for Desert Hawk UAV Incidents

Incident Number	Incident Type	Description	SA Components(s): *m*'s awareness of…
1	Crash	Winds caused loss of aircraft stability too quickly for *m* to take control	• *n*'s operational logic • *n's* weather
2	Crash	Weather-related problem during landing	• *n*'s weather
3	Crash	Wind speed unknown	• *n*'s weather
4	Crash	Aileron / V-Wing got stuck and airplane wouldn't level	• *n's* operational logic • Degree to which *n* can be trusted
5	Stuck in orbit	Operator unaware UAV was stuck in an orbit	• *n*'s operational logic • Mission progress of *n*
6	Multi-UAV, Multi-operator night flight confusion	Both m_1 and m_2 shouted/ran across the room multiple times to avoid in-flight and landing collisions.	• Activities of *M* • Spatial relationships between n_1 and n_2 • Mission progress of n_1 and n_2

7	Landing Zone Selection	Prior to flight, *m* selected a landing zone atop a building due to zooming in too much on the map. (Map was too pixilated.)	• Spatial relationships
			  o between *n* and points on earth
			  o between *n* and terrain
			• Predicted spatial relationships

8	Launch Point Coordination	*m* had difficulty knowing the precise location of the launch point.	• Spatial relationship between *n* and points on earth

9	Infrared Camera Usage	*M* was not always able to remember that images were inverted, and that camera controls were reversed when using one of the sensors.
		Note: many similar incidents observed.
			• Spatial relationships
			  o between *n* and points on earth
			  o between *n* and terrain
			  o between *n* and targets
			• Predicted spatial relationships

10	Consistency / Veracity between Camera and Control Displays	The two displays reported inconsistent altitude data and erroneous GPS status.
		Note: many similar incidents observed
			• *n*'s health
			• Spatial relationships
			  o between *n* and points on the earth
			  o between *n* and terrain
			• Mission progress of *n*

stamps in the left column and SA decomposition categories in the right column. Then at each time stamp, the experimenter would note which awareness information was being used and which was lacking: possibly using one of the SA measurement techniques that requires interrupting the pilot's task such as a tailored SAGAT (Endsley, 1998) test if the experiment was done using a simulated UAV. If an incident occurs, the experimenter would note the time and add additional notes. Gathering data in this way throughout multiple flights would elicit problems pertaining to specific awareness components, enable experimenters to compile statistics on the frequency of problem occurrences, and help provide a more nuanced picture of pilots' awareness at any given point in time.

Based solely on observations and some follow-up questions after the flights, we also found it difficult to understand how pilots mentally processed 3D spatial awareness relationships, including predicting where the aircraft would be flying in the next few minutes. To further probe the nature of these awareness components, experiments could be designed to resemble those described in the Cognitive Mapping literature (Johns and Blake, 2001), in which subjects are asked to perform distance judgment tasks, draw a sketch map, take a spatial abilities test, etc. This type of experiment would also be more suited for use with a simulated rather than actual UAV.

8. CONCLUSIONS

We developed a human-UAV awareness decomposition that goes beyond characterizing problems as "a lack of SA" to provide insight into the types of awareness that are lacking or insufficient. We were able to associate components from the human-UAV awareness decomposition with incidents in which trainee UAV pilots experienced difficulty completing their missions. Our analysis provided the impetus for several recommendations for improved interfaces. We feel the human-UAV awareness decomposition could be used by others as both a means of stating awareness needs of UAV operators and as a tool to help evaluate whether those needs were met.

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