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Awareness in Unmanned Aerial Vehicle Operations

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Abstract

Despite the name Unmanned Aerial Vehicle (UAV), humans are integral to UAV operations. Since the UAV's operator interface is the primary facilitator of human-vehicle communication and coordination, a carefully designed interface is critical for successful UAV operations. To design an effective interface, it is essential to first determine the information needs for both the human and UAV components of the UAV system. We present the Human-UAV Awareness Framework, which we developed to inform UAV system design by detailing what information components should be provided to the human through the operator interface and to the vehicles as part of their onboard systems. Since there are a variety of UAV system designs, including a number of different possible human-UAV control schemes, the paper outlines the particular types of information that would be needed for two possible UAV system contexts: a base case, which assumes one human controller and one UAV, and a general case, which assumes *n* human controllers and *m* UAVs. The paper discusses several practical considerations involved in applying the framework to UAV system design, including the level of automation of the UAVs, potential human-UAV control schemes, humans' roles, and interaction with UAV stakeholders.

Introduction and Motivation

Unmanned Aerial Vehicles, or UAVs (which are more accurately called Uninhabited Aerial Vehicles), are becoming critical to modern military command and control operations. The wide variety of UAVs—from a 50 gram AeroVironment Black Widow micro UAV to a 22,900 lb. Global Hawk high altitude, long endurance UAV—enable a range of sensor, and increasingly munitions, capabilities that facilitate a diverse set of missions (FAS, 2007). Beyond military operations, sheriffs and police departments are anxious to employ UAVs (Bowes, 2006), and the Tactical Aerospace Group of California, USA is offering unmanned helicopters for sale as crop dusters (TAG, 2007). Draganfly Innovations Inc. is marketing their Draganflyer X6 Helicopter for photographers, video production, construction site inspection, police, military and education use (Draganfly, 2008).

Though "unmanned," the success of a UAV mission relies heavily on human operators, human-human and human-machine communication, and coordination of human and machine activities. In a study by Tvaryanas et al. (2005), it was found that a significant number of the UAV mishaps that occurred over 10 years of U.S. Army, Air Force, and Navy/Marines UAV operations were due to human factors issues such as workload, attention, and crew coordination and communication. The UAV operator interface is the primary facilitator of the human-machine communication and coordination, and increasingly, of the human-human communication and coordination. Thus, designing an interface that provides an operator with an appropriate level of awareness of the activities of the UAV under his or her control and of the other operators involved in the mission is critical to help minimize information overload, distraction, miscommunications, and coordination breakdowns.

While supporting operator awareness requires more than simply providing information, we maintain that understanding information needs is a critical prerequisite for providing appropriate awareness to human operators and intelligent systems. Unfortunately, few UAV-specific guidelines exist to help system designers determine what information should be provided to UAV operators to promote awareness, and at what level of detail it should be provided. Displaying all available information, especially in raw data format, can cognitively overload an operator (Buttigieg & Sanderson, 1991; Smith, 2006), especially under time pressure and when operators are expected to control multiple UAVs (Cummings & Mitchell, 2006).

While the (inhabited) aviation and air traffic control literature is replete with studies of awareness that can inform work on UAVs (e.g., Endsley, 1988), piloting a UAV is very different from piloting an inhabited aircraft. UAV pilots lack:

- the proprioceptive cues used by pilots of manned aircraft to feel the shifts in aircraft attitude or changes in engine vibration signaling different speeds or even engine trouble,
- a wide field of view of the aircraft's environment, and
- the patterns of reaction taught in rigorous pilot training programs (if they are not licensed general aviation pilots).

Due to these differences, we have found it useful to draw upon studies of awareness in ground-based human-robot interaction awareness (e.g., Drury et al., 2003; Scholtz et al., 2004)[1]. After all, UAVs are airborne robots.

However, even these ground-based robot studies lack guidelines that address the types of information needed by human team members about each other during operations. There are many studies in the Computer Supported Cooperative Work (CSCW) discipline designed to determine awareness of collocated and/or distributed collaborators' activities (e.g., Carroll et al., 2003; Hill & Gutwin,

1. Note that when we draw from the ground-based robot literature, we adapt the results as needed to accommodate the three-dimensional airborne environment versus the two-dimensional ground environment.

2003; Millen et al., 2005; Carroll et al., 2006), but little of this knowledge has yet been applied to the UAV domain (a notable exception is Cooke & Shope, 2005).

This paper addresses the issue of better characterizing awareness needs in UAV operations by proposing a Human-UAV Awareness Framework. This framework was developed to inform the design of UAV operator interfaces, as well as the design of UAV onboard systems. The purpose of this framework is to help system designers improve UAV operators' understanding of the UAV and its environment as well as to provide improved awareness of distributed team members' activities (Carroll et al., 2003; Carroll et al., 2006; Scott et al., 2006).

The framework described in this paper takes into account the work on UAV situation awareness architectures done by Adams (2007) and Freedman and Adams (2007) and significantly extends the decomposition of UAV-related situation awareness originally proposed in Drury et al. (2006) in ways that will be described below. To extend its utility, the framework presented in this paper incorporates additional practical considerations, such as addressing the interaction between the level of automation (Parasuraman et al., 2000) of a UAV platform and the Human-UAV awareness components. The updated framework also addresses the interaction between possible UAV control schemes, UAV team structure, and the level of information detail of the Human-UAV awareness components.

The next section describes our approach for developing the framework, followed by sections describing the base case and general case. Finally, we discuss how to apply the framework to UAV system design, including an example of using the framework.

Approach

Since the current effort aims to correct the shortcomings of our original UAV-related situation awareness decomposition, it is useful to understand how that earlier decomposition was developed.

We started with the base case: one human directing one UAV. We determined base case components by combining information obtained from directly observing operators during UAV exercises, reading exercise chat logs, and conducting expert interviews. We chose these information sources because they were used successfully in previous research (Boiney, 2005) of time-sensitive situations such as those that occur when UAV operators have little time to obtain updated awareness information before redirecting their aircraft.

During observations of live operations we chiefly noted where operators' attention was focused and what information cues they relied upon to make decisions. We noted what questions UAV operators asked of other exercise participants in chat logs. During interviews we asked operators what type of information they needed when conducting missions and how they used the information. We also showed the framework to a subset of the operators to obtain feedback and validation. While most UAVs were directed by teams of operators, we concentrated on noting the interaction between each operator and the aircraft to determine the base case. Finally, we obtained our own UAVs and flew them to understand awareness issues first-hand.

To develop the general case, *M* humans and *N* UAVs, we observed teams of people directing one UAV and, in one case, four UAVs simultaneously. Because multi-UAV operations are still rare we also drew upon our previous work with operators who direct multiple ground-based robots. Finally, we flew two and three of our own UAVs simultaneously.

The resulting decomposition had four parts, in recognition of the fact that multiple humans and UAVs may be working together and each may need information about the other's identities and activities during operations:

- Human-UAV awareness: what the humans need to know about the UAVs.
- Human-human awareness: what the humans need to know about each other.
- UAV-human awareness: what information the UAVs need about the humans.
- UAV-UAV: what information the UAVs need about each other.

Although useful, we felt that our initial decomposition could be improved. In particular, it did not provide enough emphasis on awareness of overall mission goals. Also, it provided little guidance regarding human-human awareness. Further, it did not include awareness of the UAVs' capabilities, and it was insufficient for handling predictive awareness (analogous to Endsley's (1988) Level 3 situation awareness).

Finally, the Human-UAV Awareness Decomposition did not address the effects of different UAV aircraft types and system configurations on the required awareness information. For example, if operators are working with a highly autonomous UAV, they will not need to be aware of as much information as if they are hand-flying the aircraft. If operators are working closely together, they will need to know more about each other, and each others' tasks, than if their work is only loosely coupled (i.e., interrelated). Variations in possible team structures may also affect the types of awareness needed during UAV operations.

Thus, we mined the literature cited above to bring the concepts of mission awareness, levels of automation, and team cooperation into the Human-UAV Awareness Framework. As a way of determining the utility of the resulting framework, we used it to characterize the awareness deficiencies of ten incidents observed during a training course for Desert Hawk UAV operators.

Human-UAV Awareness Framework: Base Case

In the simplest case, one human and one UAV work together. Each requires certain types of information about the other to efficiently and effectively complete their joint work. We list the base case Human-UAV awareness decomposition below, assuming that the aircraft employs a typical level of automation. That is, the UAV employs waypoint-following and a few pre-programmed behaviors such as "land immediately" or "return to home." We deliberately put aside for the moment additional considerations that affect which awareness cues are needed for which situations.

Since the human-human and UAV-UAV components are not applicable in a single-human, single-aircraft case, the base case consists of three parts:

1. The understanding that the human has of the UAV (which we call human-UAV awareness),
2. The information that the UAV has about the human (UAV-human awareness), and
3. Overall mission awareness.

BASE CASE: Given one human and one UAV:

1. Human-UAV awareness consists of the understanding that the human has of:

   <u>4D spatial relationships</u>: (geographical coordinate, altitude, and velocity over time—to capture predicted future relationships) between the UAV and:

      <u>points on the earth</u>: The operator may need to understand how far the UAV is from its pre-programmed landing point, for example, to estimate how much spare power (fuel or battery life) may be available for detours.

other aircraft: The operator needs to know that other aircraft are in the vicinity (either inhabited aircraft or UAVs external to the base case team of one UAV and one human), and how far away the other aircraft are from the UAV.

obstacles: The operator needs to understand where the UAV is with respect to natural or man-made obstacles such as mountains, other terrain, or tall buildings.

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.

operational threats: The operator needs to know about, and know the distance to, any threats to smooth operations beyond inclement weather or poor health, such as surface-to-air missile batteries.

The UAV's capabilities that impact its operations, specifically its:

sensors: UAVs may have electro-optic or infrared cameras, synthetic aperture radars, and other sensors on board. Knowing the type of "eyes" on the aircraft tells operators whether they will be able to operate in daylight and/or darkness, during cloudy and/or cloudless times.

communications links: Operators may communicate with UAVs via satellite or other radio frequency communications systems. Knowing the type of communications systems can tell the operator the range from the ground station at which the aircraft can operate.

performance envelope: In case the operator needs to hand-fly the aircraft, he/she should know the minimum/maximum speeds, maximum altitude, and maximum turn rate.

operational logic: The operator needs to have a model in his/her mind of the UAV's internal programming, so that he/she can predict the UAV's responses to various normal operating conditions. For example, when issuing the "land" command, the aircraft descends in altitude using a pre-programmed pattern. Knowing this pattern will help the operators understand whether the aircraft is operating normally.

contingency logic: The operator needs to know what will happen in response to anomalous conditions. For example, a UAV may include fail-safe programming that involves a return to a "home" point 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 can predict that the UAV will soon fly directly home.

Health of the UAV:

levels of consumables: The operator needs to know the remaining fuel or battery life.

integrity of the aircraft and equipment: The operator should be aware of any malfunctions in the aircraft or broken equipment.

Other (non-health) statuses of the aircraft:

current and predicted flight parameters: Knowing the flight path and pre-programmed altitudes and speeds at each point in the aircraft's flight plan gives the operator the ability to predict the aircraft's future behavior.

current sensor mode or sensors in use: It is normally important to know which sensors are being used to correctly interpret the data coming from the aircraft.

current autonomy mode: Operators need to know if the aircraft is expecting to be hand-flown, is proceeding between waypoints, or is executing other pre-programmed behaviors.

current availability for communications transmissions: It is important for operators to know whether the aircraft can receive new commands communicated to it.

Weather near the aircraft:

current weather: The operator needs to know current weather parameters that affect performance, such as temperature, precipitation, winds, turbulence, and icing.

predicted weather: The operator needs to understand how weather conditions will evolve over time for the areas encompassed by the anticipated flight path.

Certainty of the components: Many of the above awareness components involve information derived from certain sensors or system logic that have different associated accuracy levels, such as the location data obtained from a Global Positioning System (GPS) device. The certainty of the data should be conveyed in a form appropriate for the data, for example as a confidence interval or the probability of a predicted event occurring. This would enable the operator to properly evaluate the probability of an alert being an accurate indicator of off-nominal conditions.

2. Further, the base case includes UAV-human awareness—what information the UAV needs about the:

Human's commands necessary to direct a UAV: The UAV needs information about 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.

<u>Human-delineated constraints that may require a modified course of action or command noncompliance</u>: For example, the UAV needs to maintain information about any pre-programmed fail-safe or contingency modes such as "return to home."

3. Finally, the base case includes overall mission awareness, which is the understanding of:

   <u>The mission purpose and instructions</u>, for example, a surveillance mission that is focused on keeping a particular vehicle in view as long as the vehicle remains within certain geographical boundaries.

   <u>The customers</u> who requested the mission and their intentions.

   <u>Other stakeholders</u> who have interest in, or dependencies on, the mission.

   <u>The overall progress</u> being made towards completing the mission.

   <u>The moment-by-moment progress</u> being made towards completing individual tasks and how they fit into overall mission completion plans.

   <u>Time constraints</u> for completing the mission.

   <u>The decision points</u> for the mission and when they will take place.

   <u>Related missions</u> (if any) and relevant information such as their geographical areas, mission customers and/or stakeholders, and

any dependencies between the current mission and the related missions.

This base case definition differs from that provided by Drury et al. (2006) in several ways. Perhaps most importantly, awareness of mission purpose and progress was moved from human-UAV awareness into a standalone type of awareness that has other components as well. This approach is consistent with our original formulation of human-robot interaction (Drury et al., 2003). We developed the new components for overall mission awareness based on observing UAV operations and on controlled experiments with UAV command and control strategies (Cummings & Mitchell, 2006; Scott et al., 2006; Cummings et al., 2007; Scott et al., 2007).

We made changes to the human-UAV awareness definition by dividing it into major and minor components and adding and deleting some components. 3D spatial relationships in the 2006 definition became 4D spatial relationships in this version, so that "predicted 3D spatial relationships" could be dropped; "4D" now captures the change in 3D relationships over time. We added the 4D relationship between the aircraft and its pre-planned flight path to capture the operator's need to know whether the aircraft is deviating from its expected course. We added a major component concerning awareness of the aircraft's capabilities because operator alternatives and actions are constrained by what the aircraft can do. We added awareness of predicted weather because it is not enough to know that weather along the aircraft's route is currently acceptable. We provided additional detail in the form of minor components such as the type of health and non-health status information of which operators might need to be aware.

Human-UAV Awareness Framework: General Case

We now assume that teams of people may be directing multiple UAVs simultaneously. This means that we need to add two more major parts to the awareness definition discussed for the base case: human-human awareness and UAV-UAV awareness.

The types of awareness that human team members need regarding each other depend upon the tight or loose coupling of their work. For example, consider two operators who each direct a UAV in a rural search-and-rescue task within a relatively confined geographical area. They need to coordinate where their UAVs fly with respect to each other so that they do not inefficiently search the area or experience a mid-air collision. Their tasks would be more loosely-coupled if they happened to be searching for two unrelated people in widely separated areas at the same time. Table 1 lists potential human-human awareness components for tightly-coupled and loosely-coupled joint work.

Each person will likely be comfortable knowing more or less about their collaborators depending on how tightly coupled their joint work is and on their individual personalities. Table 1 attempts to list typical items that collaborators might want to know about one another for two cases on opposite ends of the coupling continuum.

Turning to the final type of awareness in a UAV system, UAV-UAV awareness becomes interesting when the aircraft have the ability to give commands to each other and dynamically reallocate tasks from one aircraft to another when necessary based on changes in the environment or aircraft status. To pursue a mission that takes advantage of these capabilities requires that the aircraft have a fair amount of information about each other, such as each aircraft's current location and projected path, what sensors are on board which aircraft, how high each aircraft can fly, and how long each aircraft can remain on station. In this case, a human may be involved to handle emergencies or to consume the information being sensed by the aircraft and redirect them to address emerging and dynamic mission needs.

Table 1. Components of Human-Human Awareness for UAV Team Members

Humans'…	Components for … Tightly Coupled Work	Loosely Coupled Work
Locations	Choose one or more (from less to more specific): Country, time zone, region/state, city, airbase or airport, building, room, precise geographical coordinate	From less to more specific: Country, time zone, region/state, city, airbase or airport
Identities	Role, name, UAV-related affiliation (e.g., US Air Force), rank, degree to which other team members know and trust this person	Role, UAV-related affiliation
Characteristics	Training or education, relevant experience, skill with the aircraft, decision-making authority [largely static]; fatigue level, emotional state, time left on shift [dynamic]	Skill with aircraft, decision-making authority
Intentions	Overall mission goals, immediate goals	Overall mission goals
Activities in the moment	Current task, urgency of task, tools being used, changes being made, the portion of the workspace being viewed or acted upon, focus of attention, interruptability, workload	Current task, urgency of task
Activity dependencies	Division of labor, which tasks depend upon other tasks, what resources or tools must be shared, what work must be done simultaneously by multiple people	Not applicable

Integrating these awareness components with the base case described above, we define a general case for tightly-coupled Human-UAV awareness as follows.

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, the general case consists of five parts:

1. <u>Human-UAV</u>: the knowledge that *m* has of: the identities of *N*, *N*'s 4D spatial relationships between *N* and other objects (points on the earth, other aircraft, obstacles, targets, operational threats, *N's* planned flight paths), *N's* capabilities (sensors, communications links, performance envelopes, and contingency logic), the health of *N* (levels of consumables and integrity of aircraft and equipment), other (non-health) statuses of *N* (current and predicted flight parameters, current sensor mode, current

autonomy mode, and current availability for communications transmissions), current and predicted weather near *N*, and the certainty of each of these components.

2. UAV-human: the information that *n* has about: *M*'s commands necessary to direct their activities, any conflicts among commands given to *n* by *M*, and any human-delineated constraints that may require a modified course of action or command non-compliance.
3. Human-human: the knowledge that *m* has of *M's* locations (which may be country, time zone, region/state, city, airbase or airport, building, room, and/or precise geographical coordinate), *M's* identities (role, name, UAV-related affiliation, rank, degree to which *m* knows and trusts *M*), *M's* characteristics (training or education, relevant experience, skill using the aircraft, decision-making authority, fatigue level, emotional state, and time left on shift), *M's* intentions (overall mission goals and immediate goals), *M's* activities in the moment (current task, task urgency, tools being used, changes being made, portion of workspace being viewed, focus of attention, interruptability, and workload), and *M's* activity dependencies (division of labor, which tasks depend upon other tasks, what resources or tools must be shared, what work must be done simultaneously with others).
4. UAV-UAV: the information that *n* has about: the commands given to it by *N*; any conflicts among commands given to *n* 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.
5. Overall mission awareness: the knowledge that *M* and *N* (if applicable) have about the mission purpose and instructions, customers, other stakeholders, overall progress, moment-by-moment progress towards task completion, time constraints, decision points, and related missions.

In addition to the changes to human-UAV awareness discussed in the previous section, the definition of the general case differs from that presented in Drury et al. (2006) by including an expanded human-human awareness component, based on the awareness information discussed in Table 1.

Practical Considerations for Applying the Framework

Given the significant range of UAV capabilities and platforms, from micro UAVs providing local "eyes over the horizon" support, to high altitude, long endurance UAVs providing regional surveillance or tactical support, the nature of the intelligent entities involved in UAV operations can vary greatly (Figure 1). In addition to the uninhabited aircraft and their human operators, there are also a wide variety of mission stakeholders, a sample of whom are listed in Figure 1. Each of these intelligent entities in UAV mission operations introduces important practical considerations for applying the proposed Human-UAV Awareness Framework to UAV system design. For example, the autonomy level of the UAV(s) has an impact on designing awareness components. The humans' roles and the possible human-UAV control schemes also impact the design of awareness components. Finally, awareness of the mission stakeholders is important for the humans' understanding of the overall mission context. Each of these issues is discussed further below.

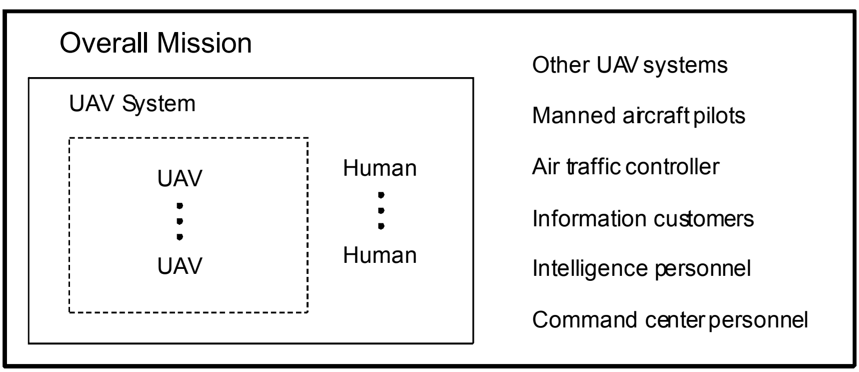

Figure 1. Overall mission context with potential mission stakeholders.

The level of automation (LOA) (Parasuraman et al., 2000) provided by the aircraft affects the types of information operators need and how detailed that information should be. For example, if UAVs can fly between waypoints and avoid obstacles with minimal human intervention then operators might only need to have overview information and alerts about abnormal conditions rather than flight-related information (health, status, weather, 4D spatial relationships, and contingency logic). In contrast, if UAVs have minimal autonomy then operators need to make many more control decisions and thus require more information to make those decisions. Clearly, the necessary awareness components (and the associated levels of information detail) will differ across systems with different autonomy levels. Figure 2 illustrates this concept by showing that, as the LOA of a UAV increases, the level of information detail (LOID) an operator requires will likely decrease. While Figure 2 describes low and high LOA and LOID, note that both can vary along a continuum.

The previous example illustrates how the UAV operator may need to take on different types of responsibilities as the LOA differs. The low UAV LOA implies that the UAV operator will take on detailed piloting responsibilities, while in a higher UAV LOA situation, the UAV operator's piloting role will be closer to that of a supervisory controller (Sheridan, 1992) or an air traffic controller.

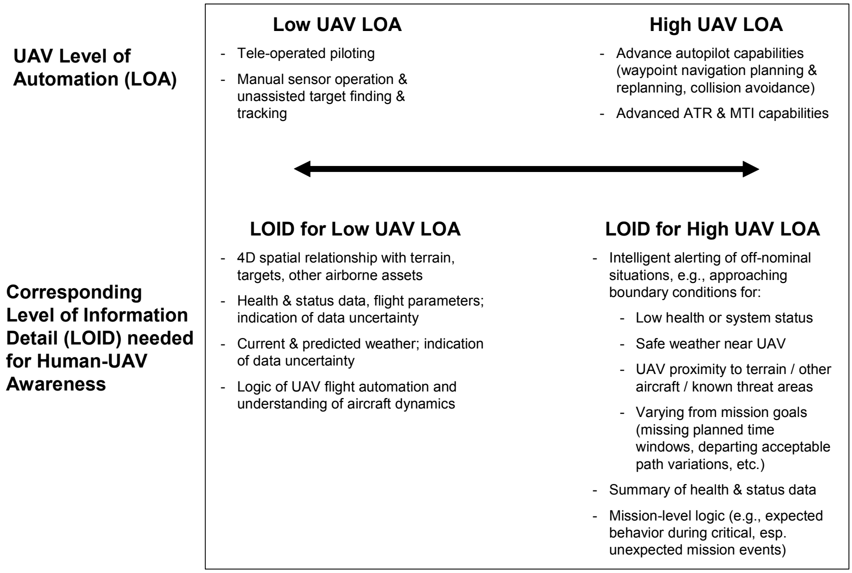

Figure 2. Potential level of information detail needed across different UAV levels of automation.

Humans in different roles will usually have different awareness needs. Scholtz (2003) defines five different types of roles for human-robot interaction: Supervisor, Operator, Teammate or Peer, Mechanic, and Bystander. As we noted earlier (Drury et al., 2006), the degree to which humans will need to know about the various components included in the framework will depend upon their role. A pilot can be considered to have Scholtz's "Operator" role, and his or her primary focus (in the absence of extensive automation) will likely be on the flight-related components of the human-UAV awareness part of the framework. A mission coordinator who is responsible for acting as a liaison between the pilot and the mission's stakeholders fits most closely to Scholtz's Supervisor role and will likely have a strong emphasis on the human-human awareness part of the framework.

A related consideration is the type of human-UAV control scheme and the corresponding organization of UAV operators that is required (or being used) in the UAV system. Not only is the number of humans and UAVs important, but it is also important to note whether they are working separately or as part of larger teams: defined as the "level of shared interaction among teams" category in Yanco and Drury's (2004) taxonomy of human-robot interaction. Figure 3 shows four potential control schemes out of the eight identified in Yanco and Drury (2004). (Unlike in their taxonomy, Figure 3 does not make the distinction between robots acting as individuals and robots cooperating with each other.) Case 1 (*m* humans – 1 UAV) is the control scheme used most often in current UAV operations. Case 2 (1 human – 1 UAV) corresponds to the base case and is typically seen in conjunction with very small UAVs. Case 3 (1 human – *n* UAVs) is largely an ideal at this point; we do not know of an operational UAV system that can routinely achieve this goal. We have seen few examples of Case 4 (*m* humans – *n* UAVs), on one occasion Case 4 was being used as a planned stepping-stone towards Case 3 operations. As illustrated in Figure 3, these control schemes have different intra-team and inter-team relationships, which result in different human-human awareness requirements, and consequently impact the UAV system awareness requirements for each control scheme.[2]

The more closely coupled two or more operators' activities are, the more awareness information they will require of each other (Pinelle et al., 2003). Thus the operators in Cases 1 and 4 will require a higher level of information detail about the current and expected activities of the operators controlling the same UAV(s) (intra-team awareness) than they will require of the operators controlling a different UAV (or set of UAVs) (inter-team awareness). The same concept can be applied to the level of coupling of the activities of the UAVs involved in the mission as well. For example, if two UAVs being controlled by different operators are used together to achieve some mission goal (e.g., one lasing a target and one striking that tar-

2. While Figure 3 illustrates potential human-UAV control schemes, we can envision a future in which UAVs control other UAVs. In that eventuality, human controllers will be replaced by UAVs to form similar intra-team and inter-team relationships.

get), the level of shared information details of each operator's activities will be higher than if the UAVs under their control are engaged in unrelated activities.

Similarly, the level of information detail that needs to be shared between intra-team members will depend on how closely coupled their activities are. For instance in Cases 1 and 4 shown in Figure 3, if one operator is responsible for piloting or route planning/re-planning and another operator is responsible for controlling or monitoring the imagery sensors, these operators will need to share a great deal of tasking information to coordinate any image capture. However, if a third operator is tasked with communicating the status of the team's mission to higher level command, this operator may only need to know the overall progress of the image capture and an estimate of when the imaging may be complete.

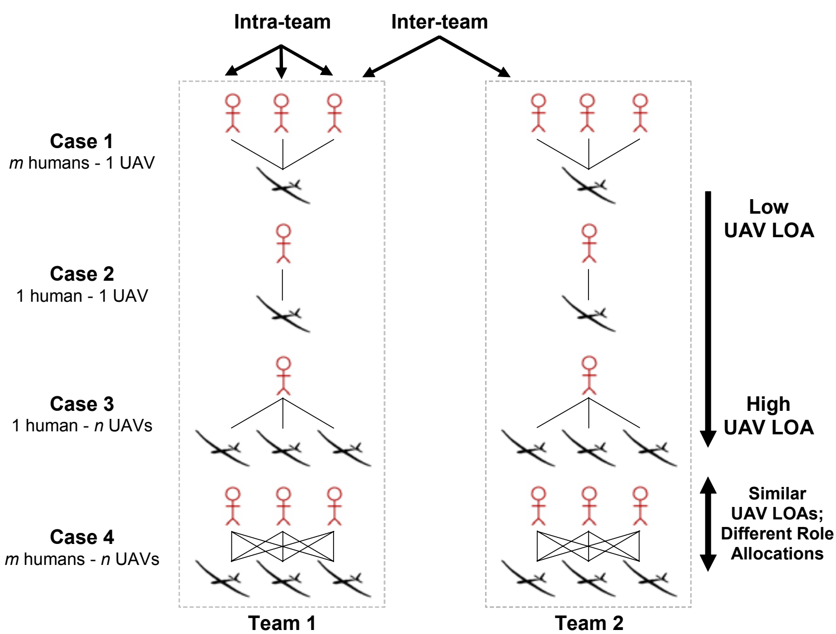

Figure 3. Potential human-UAV control schemes.

In UAV systems with high UAV LOA, similar concepts apply to the UAV-UAV awareness component of the framework. For example, the more closely coupled two or more UAVs' activities are, the more detailed awareness information they will require of each other's commands, command conflicts, tactical plans, and any exceptional conditions.

Another important consideration in applying the framework to UAV system design relates to the overall mission context. Because UAV systems are commonly used to perform missions for external customers (e.g., intelligence, surveillance, and reconnaissance (ISR) or other military support missions), the human(s) controlling the UAV(s) will need to know information about those customers and potentially other stakeholders (possibly intelligent systems) external to the UAV system. As Figure 1 shows, these external stakeholders might include ground troops, air traffic controllers, manned aircraft pilots, commanders, and operators of other UAVs (as discussed above). Thus, someone in the UAV system will need to communicate with these stakeholders and coordinate the UAV system activities to support the goals and intentions of these stakeholders.

Knowing who the external stakeholders are, and what relationships they bear to the UAV system, is part of understanding the overall mission context. The amount of coupling between the activities of the UAV system and these stakeholders will impact the level of information detail that humans and UAVs need for each of the awareness components outlined in the framework. For example, a UAV system tasked with supporting ground troops currently under enemy fire is likely to need precise information regarding the location, characteristics, and intentions of the group troops, but will probably only need a high level of detail about their moment-to-moment activities and the dependencies between those activities.

Example of Applying the Framework

In our previous work (Drury et al., 2006), we applied the Human-UAV Awareness Decomposition to observation data of UAV operations breakdowns (defined as events which potentially or actually degraded UAV mission performance). We showed that the decomposition was useful for characterizing awareness problems that contributed to the breakdowns. We similarly applied the revised Human-UAV awareness framework presented in this paper to the same set of breakdowns.

The breakdowns were collected from a Desert Hawk UAV training session. The Desert Hawk UAV (see Hehs, 2003) is a battery-operated, 7-lb, 4-foot wingspan aircraft with on-board sensors. It can be flown autonomously between waypoints, be re-tasked in flight with new waypoints, or it can be operated completely via human direction. Commands are issued via a laptop interface that provides the means for viewing its mission status. A separate video monitor displays sensor output and enables operators to capture photographs from the aircrafts' video stream.

The results in Table 2 consist of a list of the awareness components that were not well-supported by the interface for each breakdown situation. Table 2 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 (simply for reference), Incident Type (the kind of difficulty 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, we use *M*.

The first three incidents listed in Table 2 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

Table 2. Analysis of Incidents Revisited

Incident Number	Incident Type	Description	SA Components(s): *m*'s awareness of … (see Legend below)
1	Crash	Winds caused loss of aircraft stability too quickly for m to take control	• n's operational logic • n's current weather • n's predicted weather
2	Crash	Weather-related problem during landing	• n's current weather
3	Crash	Wind speed unknown	• n's current weather
4	Crash	Aileron / V-Wing got stuck and airplane wouldn't level	• n's operational logic • n's integrity of the aircraft and equipment
5	Stuck in orbit	Operator unaware UAV was stuck in an orbit	• n's operational logic • n's integrity • n's current and predicted flight parameters • Overall mission progress of n • Moment-to-moment 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 in the moment of M • Intentions of M • Spatial relationships to other aircraft (between n_1 and n_2) • Current and predicted flight parameters of N • Moment-to-moment 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
			  ○ between n and points on the earth
			  ○ between n and obstacles

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.*	• n's current sensor mode or sensors in use
			• Spatial relationships
			  ○ between n and points on earth
			  ○ between n and obstacles
			  ○ between n and targets
			• Moment-to-moment mission progress of n

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 integrity
			• Current and predicted flight parameters of n
			• Spatial relationships
			  ○ between n and points on the earth
			  ○ between n and obstacles
			• Moment-to-moment mission progress of n
			• Certainty of the n's components

Legend: m = individual human, M = all humans, n = individual UAV, N = all UAVs
Note: Incidents 1 – 5 and 7 – 10 apply to a Case 1 intra-team situation, whereas incident 6 applies to a Case 1 inter-team situation.

to high winds.) In incident #4, the pilot did not know how the aircraft's autopilot logic would handle the situation of a stuck control surface. A final example in which the operator 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 operators were 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. Operators were unsure of the aircraft's correct spatial relationships, integrity, and mission progress as a result.

Compared to the previous analysis, our new analysis identified more components, since additional components were available to be used as part of the revised framework. Thus the new framework provides a finer-grained look at UAV operators' situation awareness needs and thus more guidance for designers working on the next generation of the interface.

Conclusions

We have often heard customers of UAV systems evaluate their UAV's human interface based on whether it provides "good" or "bad" awareness (usually referred to as situation awareness). Our work developing the Human-UAV Awareness Framework has moved the discussion beyond such blanket statements about awareness to a detailed characterization of the types of awareness that are present or absent. Further, we have put into context the major influences on awareness needs: the levels of automation available to operators, operators' roles, the numbers of humans and UAVs working together, and the level of coupling between operators' tasks. In fact, further investigation of the effect of these issues on awareness needs could make for an interesting future work program. In particular, we are considering an investigation of the feasibility of using a characterization of these issues as an input to a set of heuristics whose output will be an automatically generated list of relevant awareness components.

In closing, we feel the Human-UAV Awareness Framework 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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