Human Factors Issues Relevant to Automation Design: Insights from Research on Uninhabited Autonomous Vehicles

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Executive Summary

The goal of the current report is to organize and describe some of the most salient human factors issues that were identified in a literature review of publications from Uninhabited Autonomous Vehicle (UAV) research. The issues that were included in the review were selected for their relevance to the work being conducted to automate an orchard mowing application. This relevance was determined in light of the understanding gained from the Orchard Knowledge Engineering Project (Cullen, et al., 2009a, 2009bb). Although sometimes neglected by practitioners, human factors issues in remote autonomous vehicle operation have been studied extensively as documented in this report and summarized in Table 1:

Table 1. Human factors issues from UAV operation.

1. Remote monitoring and operation of autonomous vehicles	1.1 Undermined perception of affordances
2. Autonomous vehicles' support for user goals	2.1 Automation as a means to achieve complex goals
	2.2 Capture data into higher order patterns
3. Impact of automation implementation	3.1 Appropriate support for the dynamics of human-automation interaction
	3.2 Substitution myth issues
4. Human expectations from automation	4.1 Misinformed expectations from non-authoritative sources
5. Mission endurance	5.1 The need for extended mission endurance

The first issue relates to remote monitoring or operation. When operators are not collocated with the equipment, they experience undermined perception of affordance. This hinders evaluating the ground speed of the remote vehicle and assessing the scale of elements in the explored scene. In the orchard mowing application, a large portion of actions performed by operators were of the check or monitor type. Compensation may be needed through enhanced communications channels that provide additional information.

The second issue is the support automation provides for user goals. Autonomous vehicles may enable the pursuit of more complex goals than those related solely to equipment operation. Some examples of complex goals are integrating temporal and spatial elements into decision making; solving problems, managing assets; and performing contingency planning. With support for complex goals, the number of autonomous resources being managed by an operator or supervisor can increase compared to a system where operation requires human involvement and goals are simpler.

The third issue is about the assessment of the impact of automation implementation. Automation design needs to appropriately support the dynamics created by its implementation. Alternatives to support for these dynamics include mode awareness and alerting about developing dangerous situations. This can be accomplished through seemingly feasible alternatives such as auditory alarms and tactile feedback. Key to this is also awareness about the substitution myth: recognizing that automation implementation is far more complex than simply replacing human functions with machine functions.

The fourth issue is about human expectations from automation. Misinformed expectations driven by popular movies and fiction literature are a challenge to widespread use of autonomous vehicles in the military. Capabilities that cannot be matched by the state of the art of automation are identified and requested by practitioners, and result in dissatisfaction.

The fifth issue is about extended mission endurance. The practical feasibility of multiple types of autonomous vehicles depends on extended mission endurance. Endurance that is currently in the hours may need to be extended to days, months, and even years. The orchard mowing application could use 24 hour operation for some activities if the weather allows.

This report provides details about how these issues have been studied in the context of UAV. We draw parallels to the orchard mowing project as appropriate.

Introduction

Uninhabited Autonomous Vehicles (UAVs) are platforms with increasing potential in a wide range of civilian and military applications. They not only enable practitioners to augment their capabilities in performing critical and difficult tasks, but also help them allocate human and machine resources between tasks more effectively. The research space is rich in experimental work performed to advance multiple aspects of autonomous air, ground, and underwater vehicles. This work stems from the multiple challenges that the design of these vehicles and systems presents researchers in domains related to artificial intelligence, robotics, aeronautics, sensing electronics, and computing in general. Because of the focus placed on the technical requirements of these systems and how human involvement is perceived to be minimal as they are replaced with autonomous systems, human factors issues related to these systems are often neglected (Cooke, 2006). Nonetheless, this space is rich with work conducted to better understand and support the new roles humans perform in maintaining, launching, controlling, operating, coordinating, or monitoring these systems.

The purpose of this report is to document the outcomes of a literature review conducted to identify some of the key human factors issues in autonomous vehicle monitoring and operation, as described by practitioners and human factors researchers. The goal was to provide this information in an accessible and actionable way in light of the understanding gained as part of the orchard mowing automation project (Cullen et al., 2009a; 2009b). Therefore, issues from the UAV literature are described in general and then related to the specific context of orchard mowing. This report provides details about insights gathered from five major areas of research: 1) issues associated with remote monitoring or operation, 2) support for user goals, 3) assessing the impact of automation implementation, 4) human expectations from automation and 5) extended mission endurance.

The areas of application for the issues and experiences documented in this report are diverse: military, agricultural, homeland security, air transportation, search and rescue. But as will be described in following sections, the tasks involved can also be of a varied nature.

1 Remote monitoring and operation of autonomous vehicles

One of the ways in which autonomous vehicles extend the capabilities of practitioners is through the removal of human elements from explored scenes that present threats to human lives. Scenes such as a collapsed building in search and rescue efforts or hostile locations under surveillance traditionally require the presence of practitioners to carry out their objectives but present significant threats to their personal safety. Autonomous vehicles provide a platform for practitioners to safely explore these scenes without being co-located with the vehicles. This capability also presents a challenge as the perception of a scene acquired through telecommunications is a fraction of what can be acquired with physical presence.

1.1 Undermined perception of affordances

Description: A remote operator of an autonomous vehicle is de-coupled from the scene being explored; therefore, his or her perception of affordances in the scene is significantly restricted. Some of the identified difficulties lie in scale ambiguity and assessing vehicle speed. Scale ambiguity has been experienced by operators in search and rescue applications, where they have had difficulty determining if the operated vehicle fits through a specific space (e.g., through a door frame, under a collapsed column). This difficulty is attributed to the limited perception of an environment that an operator gets through raw video feeds from vehicle mounted cameras.

The limit in perception is regarded as the “soda-straw” or “key-hole vision” problem, and occurs when a two-dimensional video feed with primarily visual cues provides a fraction of the cues provided by physical presence. Difficulty assessing vehicle speed has been experienced when a vehicle’s ground speed is misdiagnosed by an operator with the cues he or she receives through communication channels. This difficulty is attributed to the conflict between the visual cues the operator acquires through a video feed (moving vehicle) and the cues that his or her vestibular system provides, that remind the operator he or she is sitting still (Woods, Tittle, Feil, & Roesler, 2004).

Orchard project perspective: The analysis of data from the mowing application evidenced that a majority of the actions that operators reported performing as part of traditional tractor operation, are related to checking or monitoring the equipment and the environment (55%). A majority of these actions use the visual modality of seeing (70%), but operators also reported using the auditory sense of hearing (15%), the somatosensory sense of touch (14%), and the olfactory sense of smell (1%) modalities. In a remotely operated or monitored system, the pieces of information contained in the checking or monitoring actions should still be transmitted, but not necessarily through the same modalities.

Where it is appropriate for the modalities to be replicated, automation design may need to compensate for scene de-coupling. A solution for this issue is proposed by Woods et al. (2004) in the form of "functional presence", where ambiguities in the remote scene are identified beforehand and the communication channel is supplemented with additional perceptual information. This helps the operator pickup environment affordances "as-if" he or she were there. An example of this can be seen in the DARPA HART project (discussed in section 2.2), wherein high-resolution photography is laid out over a map following an aerial vehicle's flight path (Defense, 2009).

Nonetheless, there are circumstances in which automation compensation may not be of much help. There are environments with elements that humans are better equipped than automation to identify. These "negative obstacles" are distinguished with far better effectiveness by humans and are typified as depressions (puddles, ditches, holes) and drop-offs (steep down grades, cliffs, ledges, declines), as described by (Rankin, Huertas, & Matthies, 2007).

2 Autonomous vehicles' support for user goals

Autonomous vehicles and their underlying systems take over some goals that an operator who is physically co-located with the equipment would have. Goals such as monitoring fuel consumption, the equipment's position in relation to the environment, and the details of turning, can be implemented into the automation design giving the remote operator of an autonomous vehicle the possibility to pursue a different more complex set of goals and priorities.

2.1 Automation as a means to achieve complex goals

Description: Goals are integral to interactions with autonomous vehicles and systems in general, and different aspects of automation design guarantee that operators are able to evaluate if they are succeeding or failing in achieving those goals and the progress made towards them. Human-centered automation design facilitates the design of systems where the operational needs and requirements of the operator are adequately supported, in contrast to automation design that seeks to replace the operator (Sarter, Woods, & Billings, 1997).

A result of human-centered automation design is the support for effective coordination between the autonomous system and the operator. Automation design with support for effective coordination provides the means for the operator to project his intent and more complex goals into the world (Woods et al., 2004). Some examples gathered from the literature of complex goals that a remote operator could have are integrating temporal and spatial elements into decision making, solving problems, managing assets, and performing contingency planning. These contrast to simpler goals such as keeping a tractor in a path or maintaining engine RPM.

Orchard project perspective: The analysis of data from the orchard mowing application provided insights about what operators do and the purpose or goals behind those actions they reported performing. We identified that their goals are related to details of operating the equipment, the quality of job they perform, and to their own well-being as they perform the job of mowing. Operators also receive communications about keeping in mind several organizational goals: human and equipment safety, fuel and oil consumption efficiency, maintenance cost efficiency, and job quality.

In the orchard application, automation provides the means to optimize the mowing system as a whole. It also provides the means to evaluate the performance of the whole system with respect to the organizational goals. Each component of an automated system has the potential to record a wealth of data that may be aggregated and presented to the remote operator to make informed decisions that affect operation.

2.2 Capture data into complex patterns

Description: To provide the means for achieving more complex goals, an autonomous system must be capable of communicating with a remote operator in complex patterns that are more about the task domain and environment and less about details of the equipment. This mismatch in the level of complexity in which communication takes place has been identified as one of the reasons behind clumsy handoffs and surprises when systems switch in and out of autonomy (Malin, 2000).

Experiments conducted with remote operators of UAVs found that a maximum of 4 UAVs could be handled by an operator who has to handle communications about all the intricacies of operation (Ruff, Narayanan, & Draper, 2002). Another study by Cummings & Guerlain (2007) contrasted these results with those from a highly autonomous system (i.e., a management console for airborne Tomahawk missiles), that exhibits communication in more complex patterns. Information relevant to the task is captured and displayed using higher order patterns and the language of the task: suggestions of missile-target pairings, depending on matches between specific missile and target characteristics, as well as the remaining fuel and distance to be traveled.

This system supports more complex operator goals, such as evaluating time to target and distance covered for each missile, and safeguarding the integrity of the system as a whole. These goals contrast with simpler ones (that operators need not be concerned about) such as monitoring remaining fuel and steering the missile out of obstacles. Cummings and Guerlain (2007) found that with the reduced load, results from support for higher order goals and information patterns, the number of vehicles that an operator can manage effectively is in the realm of 8 to 12. This result is similar to that reported for free-flight Air Traffic Control simulations.

Complex patterns in communication were also implemented in the DARPA Heterogeneous Autonomous Reconnaissance Team (HART) project. In this project, a collection of aerial autonomous vehicles of different specifications is managed by a system to provide field soldiers with surveillance still and video imagery. The system manages details about vehicle operation and coordinates vehicle deployment while the operator uses a touch-screen to make requests for imagery from areas of interest, using the language of his task, indicating a location on a map (Defense, 2009).

Orchard project perspective: A remote operator of an autonomous mowing vehicle may benefit from more complex patterns of information displayed about equipment performance. Examples include information about the mechanical conditions of the equipment or the remaining fuel supply. This information could be displayed to the remote operator in a way that highlights how it affects progress towards the goals set for mowing (areas to be mowed, time remaining). Automation could also prevent assigning equipment to a task that it will not be able to fulfill with its current fuel supply or condition. This lets operators take more effective action based on performance information they are being given.

An important consideration is the number of autonomous vehicles that can be effectively managed by a remote operator. Even though Cummings and Guerlain (2007) suggested that 8 to 12 vehicles can be monitored with higher order feedback, research with the tasks and interfaces of an autonomous mowing application will be necessary to validate whether those numbers can be generalized to this context.

3 Impact of automation implementation

The human component of a human-machine system brings important dynamics and adaptability to the system that needs to be considered when implementing an automated system.

3.1 Appropriate support for human-automation feedback

Description: The implementation of a human-automation system and the dynamics inherent to its remote operation creates a demand for new levels of human-automation coordination. This may translate into increased feedback between the automation and the human about current actions and about future actions that automation will take, as the state of the system varies in operation (Woods et al., 2004).

Two important aspects of this feedback were identified in the literature. First is mode awareness. Mode awareness is a property of autonomous systems that implement multiple modes of operation but in which, at any time, only the current mode is visible to the remote operator. With this visibility, operators are able to track the behavior of the system and anticipate its status with less effort. The low visibility of the current system mode and the increasing autonomy in these systems, result in errors of commission when operators perform actions in one system state, thinking that the system is in other; and errors of omission, when the required human intervention is delayed or never takes place (Sarter & Woods, 2000). Examples of these types of errors can be seen when activating and deactivating cruise-control systems in automobiles. An error of commission takes place when a driver sets a speed to maintain thinking the system is activated, when it is not. An error of omission happens when it is not visible that cruise control is activated and a driver takes the foot off the gas but fails to brake for slowing traffic.

The second important aspect of human-automation feedback is related to problems or dangerous situations that may be developing. More specifically, mechanisms should be provided to inform the remote operator when automation 1) has trouble handling a situation; 2) when it is taking extreme action; or 3) when it is reaching an extreme of its authority. There are different alternatives to communicate this information to a remote operator documented in the literature such as auditory alarms and tactile feedback. Threshold-crossing auditory alarms have been found very difficult to tune in practice. They end up interfering with the task at hand, going off too soon or too late, creating a distraction for the remote operator (Klein, Feltovich, Bradshaw, & Woods, 2004).

A more promising alternative lies in the use of tactile feedback and combining it with other modalities. A study that provided users an indication of the modality and urgency of pending tasks, and that included visual, auditory, and tactile modalities found that operators dealt more effectively with interruptions of the auditory and tactile modalities, when information being communicated was additional to the main task (Ho, Nikolic, Waters, & Sarter, 2004). Another study compared distributing information across the tactile and visual modalities and also found that tactile-only and tactile-visual conditions led to higher detection rates and faster reaction times than those conditions that only used the visual modality (Sklar & Sarter, 1999).

Orchard project perspective: As part of the orchard mowing project, a seven phase model characterizing the work process was created to facilitate the analysis of information reported by operators. This model can be used in the implementation of automation to study the resulting dynamics of having automation in place and to help define new procedures that might be required for the work process. For example, the Daily Status Update phase (without the automation in place) comprises almost exclusively human activities that are constrained to a location and a time of day. This would not necessarily be the case with automation in place; therefore procedures in this phase may need to be redefined.

The Planned and Unplanned interruptions phases comprise actions that, in the current system, are mostly related to human activities. With an autonomous system in place, a new set of planned and unplanned interruptions have to be identified as they might include events of a very diverse nature: for example, obstacle detection versus the completion of a task. A majority of the actions reported by operators belong to the Mow and Transport phases of the process. Thus this might be considered when prioritizing efforts in the implementation of automation.

In relation to the use of modalities in human-automation feedback, the analysis of data from the orchard project about the modalities used to check on the equipment and environment can be used to determine if tactile alerts are feasible for mowing automation. This modality (or its combination with other modalities) should be considered if it results in a more effective communication of the piece of information identified in the analysis.

3.2 Substitution myth issues

Description: The substitution myth is a concept identified in the literature as the cause for some of the failures in automation implementation and it recognizes that such implementation is far more complex than simply replacing human functions with machine functions. Human teams and human systems involve team work and a shift in roles that is crucial not only in normal operation but also in contingencies (Woods et al., 2004). Human systems perform highly interdependent tasks and activities, and depend on one another to carry them out successfully (Sarter et al., 1997).

With an autonomous system in place, the human role is not eliminated but instead shifts from operation to that of exception handler, monitor, and manager of autonomous resources. The discussion in Section 2.2 describes a study by Sarter et al. (1997) that used highly autonomous Tomahawk missiles and found how the human role in such system moved from that of remote operator to a monitor of progress, a problem handler, and vehicle tasking.

In addition, the communication abilities that humans exhibit when interacting between themselves exceed the current capabilities of automation. Humans communicate in non-intrusive ways with the appropriate saliency and awareness of context. Current capabilities in autonomous systems make for an intrusive and impertinent communicator that repeatedly makes requests for input until these are satisfied (Sarter et al., 1997).

Orchard project perspective: In the context of the orchard mowing application, actions reported by the operators captured incidents where a tractor in a team of mowers is taken to the mechanic shop. This caused the team to re-arrange, to shift their priorities to cover the work of the missing equipment. In a similar way, mowing operators also reported incidents where they relied on other operators to communicate more effectively with their supervisors or the mechanic. When facing a language barrier, an operator quickly relied on fellow operators to find someone in the grove that had better knowledge of English and that was able to relay the desired message to a supervisor.

4 Human expectations from automation

4.1 Misinformed expectations from non-authoritative sources

Description: The Department of Defense recognizes that it faces multiple challenges in pursuing greater deployment of autonomous systems. One is misinformed expectations of capabilities and efficiencies about these systems driven by less authoritative sources such as popular movies and fiction literature. Field soldiers and other military practitioners identify capabilities that exceed the ability of current and projected technology and are then dissatisfied with the results of automation implementation (Defense, 2009).

One reason for these expectations comes from the great interest sparked in popular culture and media avenues by the laws of robotics that Isaac Asimov described in his novels (e.g., Asimov, 1950). These three laws constrain the behavior of robots in that they may not injure a human through action or omission, they must obey human orders, and they must protect their existence. These laws exceed the current capabilities of automation. Evaluating if certain behavior violates one of these laws could depend on subtleties that humans are very good at detecting (gaze, pauses in speech, hand gestures) but that currently, automation is not smart or perceptive enough to pick up on (Brooks, 2002).

Fictional robots also capture the attention of practitioners and influence their expectations through their ability to display emotions and their limitations. They are also appealing because of the consistency they display in their underlying models. This is true of popular robots such as those in the Star Wars movies. Emotion is perhaps the most important of these factors because it is what lets humans translate intelligence into action (Norman, 2004).

Orchard project perspective: The importance of this issue to the orchard mowing application may be less significant as agro-industrial applications of robotics may not suffer from expectations generated by fiction in the same way as applications in anthropomorphic robotics do. Nonetheless, expectations agricultural workers have regarding the performance of automation in a space such as orchard mowing may need to be gauged, considered, and addressed in the design of autonomous systems to guarantee their success and acceptance.

5 Mission endurance

5.1 The need for extended mission endurance

Description: As mentioned before, there are several challenges the Department of Defense identified to the widespread use of autonomous vehicles. One is the mission endurance supported by current advances in automation design. This is a capability that is needed for autonomous systems to be deemed feasible in air, land, and underwater operations. The current state of endurance enables hours of operation, whereas practitioners from different sectors envision uninterrupted operation in days, weeks and even years (Defense, 2009).

Orchard project perspective: The analysis of data from the orchard project provided insights about how the mission endurance from the current mowing system is constrained by factors such as the need for equipment maintenance and re-fueling. These issues may need to be addressed if it is intended for the autonomous mowing system to have an endurance that allows 24 hour operation, if weather conditions allow. Moreover, if remote operators are monitoring autonomous systems under different conditions (e.g., darkness), the sensors conveying information will have to designed with this range of situations in mind.

Summary

This report summarizes a collection of human factors issues identified in the research space of remote monitoring and operation of air, ground and underwater uninhabited vehicles. These issues were presented with references to the publications that they are documented in and were discussed in light of findings from the orchard mowing project (Cullen et al., 2009a; 2009b). Issues were grouped in five major categories:

1. *Issues associated with remote monitoring or operation*: Operators experience an undermined perception of affordances when not collocated with the equipment. This causes difficulty in evaluating the speed the vehicle is moving and assessing the scale of elements in the explored scene. This is particularly relevant to the orchard application as large portion of actions performed by operators were identified as being of the check or monitor type. Automation design may need to compensate for scene decoupling, through augmented communications channels that provide additional information.
2. *Support for user goals*: An autonomous vehicle ideally enables a remote operator to pursue goals of higher complexity than those related to equipment operation. This can be achieved through higher level of abstraction in communication. Some examples of complex goals are integrating temporal and spatial elements into decision making; solving problems, managing assets; and performing contingency planning. The number of autonomous resources being managed can increase with support for complex goals when compared to a system where operation requires human involvement and goals are simpler.
3. *Assessing the impact of automation implementation*: Automation design should support the dynamics created by its implementation. Alternatives to support these dynamics include mode awareness and alerting about developing dangerous situations. This can be accomplished through seemingly feasible alternatives such as auditory alarms and tactile feedback. Automation design

should acknowledge the substitution myth, and recognize that automation implementation is far more complex than simply replacing human functions with machine functions.

4. *Human expectations from automation*: Misinformed expectations driven by popular movies and fiction literature are a challenge to widespread use of autonomous vehicles in the military. Capabilities that cannot be matched by the state of the art of automation, are identified by practitioners, and result in dissatisfaction.
5. *Extended mission endurance*: The practical feasibility of multiple types of autonomous vehicles depends on extended mission endurance. Endurance that is currently in the hours may need to be extended to days, months and even years. This may be of relevance to the orchard application, as it could use 24 hour operation when the weather allows.

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