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Matthijs Amelink

Max Mulder

Rene van Paassen

John Flach
Wright State University - Main Campus, john.flach@wright.edu

COGNITIVE SYSTEMS ENGINEERING APPROACH TO SHARED SITUATION AWARENESS FOR UNMANNED AERIAL VEHICLES

Matthijs Amelink
Decis lab
Delft, the Netherlands

Max Mulder & **M.M. (René) van Paassen**
Delft University of Technology, Faculty of Aerospace Engineering, Control and Simulation Division
Delft, the Netherlands

John Flach
Wright State University, department of Psychology
Dayton, Ohio

Integration of UAVs with Air Traffic Control (ATC) is a world wide problem. ATC is already troubled by capacity problems due to a vast amount of air traffic. In the future when large numbers of Unmanned Aerial Vehicles (UAVs) will participate in the same airspace, the situation cannot afford to have UAVs that need special attention. Regulations for UAV flights in civil airspace are still being developed but it is expected that authorities will require UAVs to operate "like manned aircraft". The implication is that UAVs need to become full participants of a complex socio-technical environment and need to generate 'man like' decisions and behavior. In order to deal with the complexity a novel approach to developing UAV autonomy is needed, aimed to create an environment that fosters shared situation awareness between the UAVs, pilots and controllers. The underlying principle is to develop an understanding of the work domain that can be shared between people and UAVs. A powerful framework to represent the meaningful structure of the environment is Rasmussen's abstraction hierarchy. This paper proposes that autonomous UAVs can base their reasoning, decisions and actions on the abstraction hierarchy framework and communicate about their goals and intentions with human operators. It is hypothesized that the properties of the framework can create 'shared situation awareness' between the artificial and human operators despite the differences in their internal workings.

Introduction

There now seems little doubt that UAVs will be part of civil aviation's future infrastructure. UAVs are Unmanned Aerial vehicles that are either remotely controlled from a base station or are autonomous. Ground control of the UAV varies from stick and rudder control, to performing navigation task to mission execution by the press of a button.

The military has been using UAVs for a variety of purposes. Their missions have been characterized as the "dull, dangerous and dirty" – missions that human pilots would typically not want to fly or are not suitable to fly. There are also plenty of these missions on the commercial civil side and include environmental and geological surveys, weather reporting, search and rescue, forest-fire monitoring, border patrol and communications relaying. (Reynish, 2004)

Most UAVs are designed to fly their mission below 40,000 feet in controlled airspace, which is airspace already heavily populated by manned aircraft. In order to carry out these missions UAVs must be able to fly among conventional air traffic without demanding special handling by ATC. This would have an unacceptable impact on ATC workload and airspace capacity.

Although military UAV markets have been steadily growing, civil UAV applications have been slow to take advantage of potential applications. The slow start is, at least partially, due to the lack of a regulatory framework. Existing regulations cannot accommodate civil UAVs. A regulatory framework is being developed to ensure safety of UAV operations and allow seamless integration in national and international airspace. There are various initiatives world wide that aim to develop regulations; often they are partnerships between government and industry. Two examples are UVS-International initiated in Europe and Access Five in the United States. Despite the current lack of regulations, it is expected that regulatory authorities worldwide will require UAVs to operate identically to manned aircraft in civil controlled airspace (Avionics Magazine, October 2004). This is a major challenge UAV system design.

Concept UAV Regulations

Europe's UAV Task Force is a joint JAA / EUROCONTROL initiative to commence work leading to European regulations for civil UAVs. In May 2004 the UAV Task Force delivered: *A concept for European regulations for civil unmanned aerial vehicles*. In this report three of the guidelines that have been established during the development of the regulation stand out with respect to this research. They are repeated here shortly:

<u>Fairness</u>: *Any regulatory system must provide fair, consistent and equitable treatment of all those it seeks to regulate.*

<u>Equivalence</u>: *Regulatory standards should be set to be no less demanding than those currently applied to comparable manned aircraft nor should they penalize UAV Systems by requiring compliance with higher standards simply because technology permits. UAV operations shall not increase the risk to other airspace users or third parties. UAV operators should seek to operate within existing arrangements.*

<u>Transparency</u>: *The provisions of an Air Traffic Service (ARS) to a UAV must be transparent to the Air Traffic Control (ATC) controller and other airspace users. (…) UAVs must be able to comply with ATC instructions and with the equipment requirements applicable to the class of airspace within which they intend to operate.*

The U.S. Department of Defense faces the problem of enabling their military UAVs to fly in civil airspace. The Office of the Secretary of Defense has provided the *Airspace Integration Plan for Unmanned aviation* (2004). Two of the principles guiding their approach are repeated here:

<u>Do no harm</u>: *avoid new initiatives that would adversely impact air traffic control procedures and manned aviation.*

<u>Conform rather than create</u>: *avoid the creation of dedicated UAV regulations as much as possible. The goal is to achieve transparent flight operations in the National Airspace System.*

These guidelines and principles will have a great impact on how future UAV Systems will be designed to comply with the regulations internationally. For the most part they indicate that UAVs should fit in seamlessly with manned aviation and meet equivalent levels of safety. Only time will tell, when the actual regulations are enacted, how much room is left for dedicated UAV regulations.

All UAVs have to meet the regulations whether the UAV is autonomous or piloted from the ground. Those UAVs that depend on a communication link for control are sensitive to failure of that link. Failure may be due to e.g., atmospheric disturbances, hijacking attempts, jamming or tactical maneuvering. In any case in civil airspace, the UAV must ensure its safety and that of the other airspace users. How regulation will precisely deal with this mode of failure is unclear but it has been suggested that every UAV will need an autonomous mode that is capable of sense and avoid to ensure safety (Airspace Integration plan, 2004; UAV Task Force 2004). In the next paragraph the problems associated with developing UAV autonomy are addressed.

Another obstacle, and technological challenge, is that present UAVs cannot yet detect manned aircraft and conflict situations. Therefore they cannot safely share airspace with manned aircraft. To become accepted in civil airspace, UAVs need to have the capability to 'sense and avoid' other aircraft in their operating environment with the same level of safety as human pilots. This problem will also be addressed in the next paragraphs.

Problem Formulation

In the air traffic domain rules, procedures and regulations have centered on the way humans communicate and on human cognitive capabilities. The focus of the problem is on how human operators communicate about the meaning in the domain and build their situation awareness. For autonomous UAVs to effectively behave like manned aircraft, they need to be able to communicate about the same meaning and therefore share the same kind of situation awareness with human operators.

There are three areas of interest with respect to UAV behavior. To be a full participant in the airspace a UAV must be:

1. capable to sense and avoid other aircraft and obstacles.
2. a full participant in the ATC environment
3. able to cope with unanticipated events

1. Sense and avoid A lot of emphasis is put on 'sense and avoid' capability in the conceptual regulations because it is an important capability of critical safety concern. To us the term 'sense and avoid' seems incomplete because it omits the decision process that intermediates 'sense' and 'avoid'. Assuming that obstacles and other aircraft can be sensed, the weight of the problem is in deciding what action to take. Part of this process is assessing the situation and possibly negotiating a solution. Situation awareness plays an important role in this and the 'sense and avoid' capability is therefore seen as an integrated part of the overall autonomy and decision making architecture of the UAV.

2. Full participation in the ATC environment Controlled airspace is a complex socio-technical environment that is shared by many people that contribute to the system and are interdependent for function and safety. UAVs should become part of this environment and therefore integrating UAVs with existing ATC is not a matter of programming the optimal solutions for the problem but instead it is a matter of finding best human practice. A purely technological solution alone will not address the full scope of the integration problem; hence human factors is a core element of the UAV integration process.

Communication is the most important interface between the UAV and the ATC environment. It allows parties to share information, express intentions and resolve conflicts. It is unlikely that UAVs will communicate through speech but it will need to be able to use the concepts used in ATC and understand their meaning. How a UAV can understand meaning is related to how it can have situation awareness.

3. Unanticipated events This topic is left untouched by the concept regulations. It is the area where CSE is thought to have its major contribution. In the Airspace Integration Plan (2004) for unmanned aviation it is suggested that "Preprogrammed decision trees are built to address each possible failure during each part of the mission" (airspace Integration plan for unmanned aviation, office of the secretary of defense, 2004). Although this technique will cover a lot of failure modes in possibly a very effective way, there will always be some failures that were not anticipated by the designers. To ensure an equal level of safety as manned flight, UAVs need to be able to effectively cope with unanticipated events. To improvise and come up with new solutions to new problems requires an understanding of the structure of the work domain. The UAV needs to have this understanding / awareness.

A Domain Representation for UAVs

The difficult question is: "how to create machine situation awareness that is compatible with human situation awareness?" The answer lays in how the domain is represented internally: the UAV's mental model of the work domain has to be compatible with how human operators think of the work domain. The internal model will also determine the UAV's capabilities of dealing with the environment. We believe that part of the solution is in how people make abstractions in their work domain and that the properties of Rasmussen's abstraction hierarchy (Rasmussen, Peijtersen, and Goodstein, 1994) are central to this approach. To satisfy the requirements pointed out earlier, the abstraction hierarchy is proposed as the basis for the domain representation for autonomous UAVs.

The abstraction hierarchy is proposed as the basis for a domain representation mainly because its properties that are important to work domain analysis are also important for the intended domain representation. As described by Vicente (1999), the first important property is the psychologically useful way it represents complex work domains. The second important property is that it provides an informational basis for coping with unanticipated events. Both are shortly discussed below.

Psychological relevance The abstraction hierarchy consists of multiple domain representations on different levels of abstractions that are linked through functional means-ends relations. This type of hierarchy is explicitly purpose oriented and allows operators to deal with complexity effectively. Each level describes the domain but moving up the levels there is less detail and more purpose and meaning. Thus the top level describes the domain's functional goals which are usually abstract and the lowest level describes the physical implementation. For the air traffic domain you will find abstract terms like traffic flows, safety, and efficiency in the upper levels and more concrete terms like flight path, aircraft, and engine in the lower levels. Note that the abstraction hierarchy intended here covers the air traffic domain and not only the UAV system.

The abstraction hierarchy connects the elements of the work domain in means-ends manner so that they can be seen in relation to what their meaning is. This is the property that allows goal oriented problem solving. The problem solving itself is constrained to that which is relevant by starting on a high level of abstraction, moving down only concentrating on the subset of the domain that is connected to the function of interest. This allows for computationally economic problem solving (Vicente and Rasmussen, 1992) which is important to all resources limited agents.

To be transparent UAV decisions and actions should be based on a domain representation similar to that of the human operators. A domain representation is needed that is compatible with human thinking. The psychological relevance of the abstraction hierarchy has this implication. If the abstraction hierarchy is indeed psychologically relevant and people do reason within an abstraction hierarchy representation, it can form the common language in a socio-technical system. In other words; when a domain representation that is based on the abstraction hierarchy is successfully implemented in a UAV it should be able to deal with the domain complexity in a goal oriented way and communicate about the meaningful concepts in the domain. It should generate behavior that is compatible with the human way of dealing with the same problems. This is a first step towards man-like behavior as will be required by authorities.

Coping with unanticipated events Unanticipated events are by definition not foreseen by designers. Currently systems are not very good at dealing with these events and they form a big threat to safety. In ecological interface design (EID) the abstraction hierarchy representation provides a basis for coping with unanticipated events (Vicente and Rasmussen 1992). The abstraction hierarchy framework is used because it captures the domain complexity while it does not have built-in rules or procedures for dealing with the complexity. The work domain is described in terms of constraints that it imposes on the operator and does not describe actions or tasks to deal with the domain. When constraints are broken or not met, which will happen when the actual behavior and intended behavior differ, the representation provides a framework for goal directed problem solving.

This is in contrast to programming decision trees that address each possible failure during each part of the mission, but leave the unanticipated events unaccounted for. The abstraction hierarchy is constrained based and not rule based thus attention needs to shift from rule based reasoning to constraint based reasoning. The idea is that in combination with constraint based programming the representation can be used to deal with situations that wouldn't be captured in a rule-based knowledge system. It can be used to cope with unanticipated events.

As with EID, the abstraction hierarchy is used to support knowledge based behavior. However, it is not intended to engage in problem solving activity for every encountered situation. Rule based and skill based behavior can be much more computationally effective to apply to known solutions. To make this distinction the system will need to detect whether a known solution will be effective or if it needs to generate a new solution in a new situation. It is hypothesized that the abstraction hierarchy representation can support making this distinction.

Conclusion

The main benefit of developing this architecture is the psychological relevance it has. It is a representation compatible with human problem solving. The work domain is represented in a way that is similar to the mental model of the human operators. When the architecture is based on such a representation it is expected that the UAV will behave according to human expectations and become compatible with human interaction. The immediate benefits are that the abstraction hierarchy:

- provides a psychologically valid representation for goal directed problem solving.
- forms a common language for agents in a socio-technical domain.
- provides an informational basis for coping with unanticipated events.
- supports computationally economic problem solving.

Situation Awareness for UAVs

The next important question is: "what is situation awareness in a machine?" It is an interesting question because there is not a clear answer to what situation awareness is in a person. Before successfully integrating manned and unmanned flight it is necessary to have some understanding of how a machine can be aware of its situation and what that means. This paragraph is the result of a first assessment and explains what is though to be a useful path that will lead to UAV situation awareness.

The notion of situation awareness is hard to grasp, it is not tangible and at times seems to describe itself. As pointed out by Flach, Mulder and van Paassen (2004) it is important that we don't slip into using the description of the phenomenon as an explanation of the phenomenon.

To come more to grips with the concept of machine SA a comparison is drawn with the concept of safety. Safety is an important property of many systems we build, especially aircraft. Aircraft that are unsafe are not allowed to fly. It is a well defined property of the aircraft (by regulations) but nowhere can a component, a subsystem, a process or any 'box' be found in an aircraft that is labeled 'safety'. This is because safety is an aggregation of the properties of the components and their interactions. Safety has an abstract meaning and is not directly observable. When designing situation awareness the designer should not aim for building a box or a process that can be labeled 'situation awareness'. A UAV's situation awareness is, like safety, an aggregation of system properties, processes and their relation to the actual situation. It is reflected by the system's interactions with the environment, thus how it deals with the situation. The first step the designer should focus on is building an architecture for the system that allows it to understand the situation. Our first step is the domain representation as proposed in this paper.

Flach et al. (2004) state that an understanding of what is meant by the term 'situation' is essential for any progress toward a coherent theory of SA. The abstraction hierarchy is considered as a description of how experts organize or chunk complex information. In the same sense designing an understanding of the situation in the work domain is needed for any progress towards designing SA. And the abstraction hierarchy is proposed as a domain representation for understanding the situation; a means for the designer to chunk complex information in a way that is compatible with human reasoning.

Shared Situation Awareness

The term 'shared situation awareness' is used here to describe the capability of UAV, pilots and other operators to share their situation awareness. The importance of shared situation awareness to automation is discussed in relation to collision avoidance. Collision avoidance is very important for UAV operations because collision avoidance (sense and avoid) capability needs to be demonstrated before UAVs are allowed to fly in civil airspace. That the matter is more complicated than equipping UAVs with a Traffic Collision and Avoidance System (TCAS) is illustrated by what is referred to as the Ueberlingen midair collision. Nunes and Laursen (2004) describe the events of that night and identify a number of contributing factors, ranging from system malfunctions to human factors issues that took the safety redundancy out of the system. Under such circumstances it can be anticipated that some errors remain uncaught but what is striking is that TCAS, a system designed as a last safety measure to resolve a traffic conflict when all else failed, was unable to prevent a fatal accident. On board commercial jets TCAS interrogates the transponders of nearby aircraft. When a possible collision is detected one pilot is told to climb and the other to descend and thereby resolve the conflict. However, according to Nunes and Laurson (2004) TCAS itself was a contributing factor that led to the accident.

The Ueberlingen Accident

On the night of the 1st of July 2002 a midair collision took place above Lake Constance, Germany. The collision involved a Boeing 757 en route from Bergamo to Brussels and a Tupolev-154 that was flying form Munich to Barcelona. Both aircraft were equipped with the Traffic Collision Avoidance System (TCAS). The aircraft flew at the same altitude (FL 360) and their trajectories intersected at an angle of 90 degree above Lake Constance, they were on a collision course. Just seconds *before* TCAS gave both pilots a resolution advisory the air traffic controller at the Zurich Area Control Center contacted the T-154 and instructed the pilot to *descend* to FL 350 to avoid collision. Seconds later, TCAS detected the possible collision and instructed the Tupolev pilot to *climb* and the Boeing pilot to descend. The Russian Tupolev pilot received conflicting commands and decided to obey the air traffic controller and to ignore TCAS. The Tupoloev descended to FL 350 where it collided with the Boeing that had followed the TCAS advisory and also descended to FL 350. All 71 people were killed. TCAS conflict resolution is based on the assumption that both involved aircraft actually follow the resolution advisory. Free interpretation of the TCAS is incompatible with TCAS philosophy because it does not account for situations where one aircraft does not follow instructions as was the case in the Ueberlingen accident.

When there is a conflict between ATC and TCAS, European pilots are advised to follow the TCAS advisory. In contrast Russian pilots are trained to take both the ATC commands and TCAS advisory into account before making a decision. The British pilot of the B757 followed TCAS and descended to FL 350, and the Russian pilot of the T154 chose to ignore TCAS and follow the ATC command to descend to FL 350 as well. Why the Russian pilot took this decision at that time will remain unknown but it does point out that there must be arguments for pilots to assume that ATC is in control and has priority over TCAS. The fact that the Russian pilot had not contacted the air traffic controller about the conflicting commands suggests that these arguments might be quite strong. If it is indeed the case that pilots can have good reasons to believe that they should not obey TCAS the assumption that all aircraft follow the traffic resolution becomes unreliable. Unreliable because the parties involved based their situation awareness on different assumptions.

The air traffic controller did not know that the given command to descend was in conflict with the resolution advisory that TCAS issued seconds later. The Russian pilot in the T-154 probably thought that the air traffic controller was resolving the conflict and decided to obey the controllers command without confirming this. The British B757 did what made the most sense to him to avoid a possible collision and followed the TCAS advisory. The assumptions they made, made sense to their own understanding of the situation but were incompatible with one another.

The described TCAS problems can be translated into a lack of *shared situation awareness* as a contributing factor. What the TCAS contribution to the accident points out is that the situation awareness of one airspace user is not enough. The situation must be shared by all involved parties, they must have the same understanding of the situation and work domain; they must share situation awareness.

With respect to TCAS, improvements could be made to make sure that the controller has the same information as the pilots when a TCAS alert is triggered. One way of doing this could be to automatically inform ATC that a conflict is detected and that what advisories have been issued.

California Crisis

The above story cannot really be told without telling about how TCAS saved the day in a potential disaster unfolding in the southwestern U.S. skies on Tuesday 14th of September, 2004. The crisis occurred at the Los Angeles Air Route traffic Control Center in Palmdale California at around 5 pm. The center that is responsible for aircraft flying above 13000 feet suddenly lost contact with all 400 aircraft in 460 000 square kilometers of airspace over California and parts of Arizona, Nevada and Utah including the busy McCarren International airport in Las Vegas (Geppert, 2004). The cause was a software bug and left aircraft in the area without ATC guidance to keep them separated. Quick thinking controllers used mobile phones to alert other traffic control centers and the airlines that their aircraft were on a collision course but the real life saver was TCAS. Commercial jet pilots were able to avoid collisions by following the issued TCAS advisories. That evening no collisions took place despite the large number of aircraft involved.

This incident shows us that communication does not by definition enhance shared situation awareness. In this event the lack of communication gave the pilots no other choice but to rely on the TCAS resolution advisories for collision avoidance. Given the situation it was safe for pilots to assume that the other involved pilots relied on TCAS for collision avoidance as well and that it was their highest priority. The lack of communication made all pilots assume the same thing about their situation which resulted in a high degree of shared situation awareness and the safety of 400 airplanes.

Discussion and Future Work

The problem of UAV integration is a much larger problem than just fitting UAVs with clever 'sense and avoid' equipment. Because UAVs will be required to operate like manned aircraft, human factors is a core element of the integration process. UAVs need to have situation awareness like human pilots and they need to be able to share their world understanding with people. The abstraction hierarchy has been identified as a valuable framework for representing the work domain and the situation, i.e. the constraints shaping behavior. It is hypothesized that the abstraction hierarchy as a domain representation will form the basis for goal directed problem solving and dealing with unanticipated events.

Future research will focus on how the abstraction hierarchy can be formalized into software and used to reason about the world and engage in goal directed problem solving activities. The representation will be compatible with the human way of reasoning about the work domain. It can form the common language between multiple operators in the domain, including human (actors) and artificial operators (agents). When actors and agents make their decisions based on the same goal directed representation of the work domain they will be able to understand each other's behavior despite their different internal workings. Eventually this should lead to shared situation awareness which is a state in which multiple operators (artificial and human) have a great deal of similarity between their understandings of the situation.

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