AUTONOMY BASED HUMAN-VEHICLE INTERFACE STANDARDS FOR REMOTELY OPERATED AIRCRAFT

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Introduction

Remotely Operated Aircraft (ROAs) (also known as UAVs) are a growing presence in world-wide civil airspace, however, without an associated set of Communication, Navigation, and Surveillance (CNS) standards, future growth will be jeopardized. The recent deployment of the USAF's Global Hawk from the US to Australia, as well as the planned visit to the 2002 Berlin airshow highlights the growing maturity and capability of ROAs. Civilian ROAs are also increasingly popular with over 42 civil and military ROAs in development/production operating in a variety of missions [1]. For at least a portion of their mission, ROAs often share civil airspace with other air traffic, therefore they must achieve levels of CNS safety and performance equivalent to those demanded of conventional aircraft. This implies that ROAs will have to comply with the requirements of existing civil CNS standards.

Unfortunately, rules and standards for inhabited aircraft are not always appropriate for ROAs. For example, specific flight director requirements will not apply if the operator cannot manually fly the ROA, but is only responsible for entering navigation waypoints. Due to a lack of specific ROA rules and certification standards, these aircraft currently require special certificates of authorization from civil aviation authorities prior to flying in civil airspace. This certificate of authorization process is too slow and cumbersome to support widespread ROA operations. For example, difficulties associated with gaining access to civil airspace have been cited as a major reason for NASA's decision to cancel a set of ROA demonstration missions scheduled for 2002 [2]. As a result, there is an urgent need to adapt conventional aircraft standards for the certification of ROA CNS functions. Since the major differences between ROAs and conventional aircraft lie in the relationship between the vehicle and the operator, this paper will focus on Human-Vehicle Interface (HVI) requirements. This adaptation process must proceed in a purposeful and principled manner in order to ensure that it captures the essential difference between ROAs and conventional aircraft which will be required to achieve target levels of safety and performance.

The most obvious difference between ROAs and conventional aircraft is the location of the operator. Since the ROA operator is physically separated from the vehicle, peripheral visual and somatosensory cues are not available. While this information can be important, the critical difference between ROAs and conventional aircraft lies in the allocation of functions and roles between the human operator and automated systems. While some ROAs, such as Predator, are flown by a remotely located human operator using a stick and rudder, others are much more autonomous and allow the operator to primarily supervise, rather than control ROA performance. The roles and associated information requirements of the human operator will vary with vehicle autonomy.

This paper proposes a process for developing CNS human-vehicle interface standards specifically adapted for ROA aircraft. It is likely that no single standard will fit all ROAs, but rather these standards must be based on vehicle autonomy. The following sections will describe operator roles and information needs based on level of autonomy. We will first discuss the implications of varying levels of vehicle autonomy and propose a framework for categorizing ROA autonomy based on Billings' [3] taxonomy. Next, we will discuss operator information needs based on Sheridan's [4] model of supervisory control. Finally, we will briefly describe civil CNS standards, suggest a methodology for adapting those standards for ROA operations, and identify some of the issues that may require further study.

Vehicle Autonomy

While it may be tempting to think of ROAs as completely autonomous vehicles, it is important to remember that they are still controlled by a human operator. As pointed out in the previous section, the role of the human operator varies greatly between ROAs. It is not our intent to describe and categorize existing ROAs based on autonomy, but rather we will describe a general framework for such a categorization process.

Table 1. A Continuum of Vehicle Autonomy [3].

Automation Management Mode	*Human and Machine roles*
Autonomous Operation	Operation in accordance with instructions provided by system designers; no human attention or management required (human intervention may be impossible).
Management by Exception	Automation possesses the capability to perform all required actions and will perform all actions unless the human operator takes exception by manually intervening or reprogramming automated systems.
Management by Consent	Automation, once provided general goals, operates autonomously, but will not act until and unless human operator provides consent
Management by Delegation	Once human operator provides specific instructions, automated systems will follow those instructions unless it is not capable of executing them.
Shared Control	Human provides control inputs that are modified and shaped by automated systems.
Assisted Manual Control	Human operator provides control inputs that are implemented by automated systems.
Direct Manual Control	Human operator physically controls the system.

Humans and machines can share system control responsibilities in many ways. Billings [3] has developed a comprehensive list of different methods of implementing automation in the aviation domain, drawing on the work of both Sheridan [4], [5] and Wiener [6].

Table 1 describes Billings' levels of autonomy, referred to as automation management modes as well as the associated human and machine roles. These automation management modes cover the spectrum from fully manual to completely automatic control. In general, the authority (ability to provide control inputs that the human operator cannot override) and autonomy (ability to act without human input) of automated systems increases as the level of automation goes from manual to full automatic control.

Each level of vehicle autonomy provides its own unique human-vehicle interface requirements. Take collision avoidance as an example. In *a direct manual control or Assisted manual control* system, operator roles and information requirements are essentially similar to those for conventional aircraft, i.e., the pilot is responsible for implementing a collision avoidance maneuver. Under a *shared control* approach human inputs may be modified by automated systems. Thus, the operator would need to understand not only the location of intruder aircraft and prescribed collision avoidance maneuver, but to also understand (or the collision avoidance logic would need to take into account) how human collision avoidance commands would be modified by the automated systems. Under *Management by Delegation*, the operator could choose to delegate collision avoidance to the automated systems. In this case, vehicle displays would have to ensure that operator was aware of whether or not automated systems had been given responsibility for collision avoidance, and also indicate when automate systems were unable to fulfill collision avoidance responsibilities. Under a *management by consent* approach, the vehicle would request operator permission prior to automatically initiating a collision avoidance solution. Therefore, system design would have to ensure that the operator was provided sufficient information and time to make an informed decision regarding the suitability of proposed vehicle action (so called “informed consent’) [3]. Research indicates providing informed consent may be difficult in time pressure situations [7]. The implementation of a *management by exception* approach would allow the vehicle to initiate automated collision avoidance maneuvers, but would provide the operator the opportunity to intervene afterward if he/she decided the maneuver was inappropriate. This implementation would remove the requirement for operator approval prior to an automated collision avoidance maneuver; however, it may place even greater demands on the human operator by requiring recognition of what the system is doing, why it is doing it, and providing a means to intervene if necessary. Finally, in true *autonomous operation*, it is unclear what information (if any) should be provided to the operator, since there the operator cannot override machine actions.

It is important to realize that ROAs can operate at different levels of autonomy based on task or mission segment. For example, aircraft position reporting may be completely automated, while due to concerns over the reliability of intruder alarms, collision avoidance may require manual control by the human operator. The process of adapting CNS standards for ROAs will require an analysis of each CNS function to ascertain the level of autonomy associated with that task. Based on this level of autonomy, ROA standards must address associated human-vehicle interface considerations and requirements identified in the previous discussion.

Supervisory Control

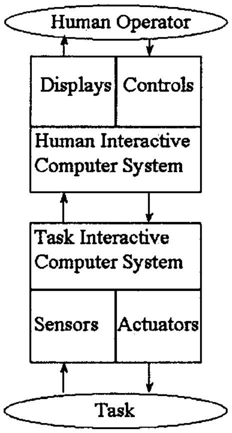
Many of the HVI considerations described above spring from the ways in which high levels of vehicle autonomy changes the role of the human operator. One of the biggest changes associated with increasing vehicle autonomy is the switch from manual control to supervisory control. This section will discuss how increasing levels of vehicle autonomy changes the roles and information needs of the human operator.

Operator Roles

As has been documented in conventional aircraft, as vehicle autonomy increases, the role of the human operator changes from that of a manual controller to a supervisory controller [4], [8]. In other words, instead of providing stick and rudder inputs, the human operator provides higher level system goals such as navigation waypoints and target speeds, while the automated systems determine the means to achieve those goals.

Figure 1 depicts the basic supervisory control processes based on Sheridan’s model of supervisory control [4]. As a supervisory controller, the operator provides system commands to a human interactive computer (HIC) which consists of system status displays and data input devices. In a typical ROA, the HIC may include displays of vehicle attitude, altitude, and navigation status, and controls that allow for entry of navigation waypoints, airspeed, and altitude. The Human Interactive Computer passes these goals to the lower level Task Interactive Computer (TIC) which translates these higher level goals into a set of commands to the actuators that will produce the desired system performance.

Figure 1. A Model Of Supervisory Control



While this model assists in understanding the relationships between the human operator and vehicle components, a more detailed analysis of specific operator tasks is required in order to determine the HVI requirements associated with each role. Sheridan identifies five basic human roles in supervisory control [4]:

- Planning
- Teaching
- Monitoring
- Intervening
- Learning.

In the *planning* role, the operator decides how to implement a desired change in vehicle performance. For example, given a directed change in vehicle routing, the operator must decide which control variables to manipulate (i.e., to change vehicle heading or insert new waypoints), develop criteria to assess system actions (i.e. determine which displays will best provided feedback on the desired action), and determine constraints on the required activities of the automated systems (i.e., will the new routing be compatible with onboard navigational capabilities such as Required Navigation Performance (RNP)). The planning process provides the basis for instructing automated systems and monitoring subsequent system behavior. Since the results of planned changes to system behavior may be hard to visualize or understand, ROA displays may have to provide the capability to indicate predicted changes based on planned inputs [9].

Once a plan has been developed, the pilot "*teaches*" the automated systems by providing the appropriate targets/instructions to automated systems. Due to the coupling between automated systems it is possible for data to have unintended consequences, for example, in conventional aircraft changes to the horizontal navigation profile can have unintended consequences for the vertical profile [10]. Research indicates that such situations in which automated systems do more than expected are particularly difficult to detect. As a result, HVI standards should require ROA displays to highlight all projected changes that will result from operator inputs.

After providing input to the automated systems, the pilot then *monitors* system performance to ensure vehicle performance matches operator expectations. Monitoring refers to all activities involved in adjusting system performance in response to small deviations (trimming), as well as fault detection and diagnosis. In the conventional aircraft, the pilot relies primarily on information presented on the Primary Flight Display (PFD) and Navigation Display (ND) to monitor system performance. Research indicates that high levels of automation have fundamentally altered operator scan patterns. Instead of a general scan of vehicle displays, operators tend to employ a knowledge based scan pattern in which they scan specific displays to confirm that vehicle performance matches expectations [11]. Studies also indicate that scanning can be relatively ineffective in detecting undesired performance of automated systems [7], [12]. It appears that if improper vehicle behavior is not detected during the initial knowledge based scan immediately following data entry, deviations from desired performance may be rather difficult to detect [7]. As a result, ROA displays must support operator scan patterns. They should direct operator attention to relevant variables, and provide a means to easily ascertain the propriety of command inputs immediately after data entry.

If the operator detects undesired system performance, he/she must decide whether/when/how to *intervene* with machine performance (due to, for example, task completion, machine requests for assistance, or undesired system performance). Unlike conventional aircraft, highly autonomous ROA aircraft may not allow the operator the option of assuming manual control (for example, Global Hawk only provides a limited manual control capability). If the operator cannot intervene to affect a desired change in vehicle performance (e.g., if the operator is unable to change the rate of climb/descent to avoid a collision), then an intelligent automated detection/intervention system may be required. Additionally, if the operator is able to intervene in system behavior, the HVI must facilitate operator intervention by providing for quick and low workload method to re-instruct/reprogram automated systems. A survey of pilot experiences with highly automated conventional aircraft indicate that it is often difficult to reprogram automated systems when manual intervention is not desired [13].

Finally, based on the given plan, inputs to the system, system behavior, and interventions (if any), the operator learns lessons that may be applied to system control in future situations. In order for the operator to learn the appropriate lessons, the ROA HVI must support an accurate mental model of the system and allow the operator to understand why the system behaved as it did.

In summary, at higher levels of ROA autonomy, the operator will function as a supervisory as opposed manual controller. HVI standards for ROAs must ensure that ROA displays/controls support the operator in each of the five roles – planning, teaching, monitoring, intervening, and learning. The above discussion summarizes some of the general HVI considerations associated with each operator role. In general, ROA displays must support operator mental models, provide predictive information regarding vehicle performance, and support monitoring of vehicle behavior.

Information Needs

In addition to the HVI requirements identified for specific operator roles, research in supervisory control systems provides some additional, more general, HVI considerations. As a supervisory controller, the human operator is responsible for coordinating human and machine tasks and goals [7]. Successful coordination requires the operator to understand the tasks and goals of the automated systems and be able to predict how the system will respond to environmental perturbations as well as operator input [14]. Breakdowns in human-machine coordination may be avoided or minimized to the extent that operator can understand and predict vehicle behavior.

It is important to remember that the information required to function as a supervisory controller may be different than that required to manually control the same system. In a manual control system, the operator directly processes error information (deviations from desired performance) and provides input to return to the desired state. In this light, vehicle attitude, altitude, and airspeed information is critical to manual system control. In a supervisory control system (i.e. an ROA operating at a high level of autonomy), the operator needs to understand the goals the automated systems are attempting to achieve, the control methods used to achieve those goals, and the extent to which system performance matches operator expectations. Since the automated systems are performing the inner loop control functions (i.e. control surface activation), attitude and airspeed information may be less important than automated system status (i.e. mode) and system goals (i.e., performance targets and flight control computer functions (hard flight envelope limits).

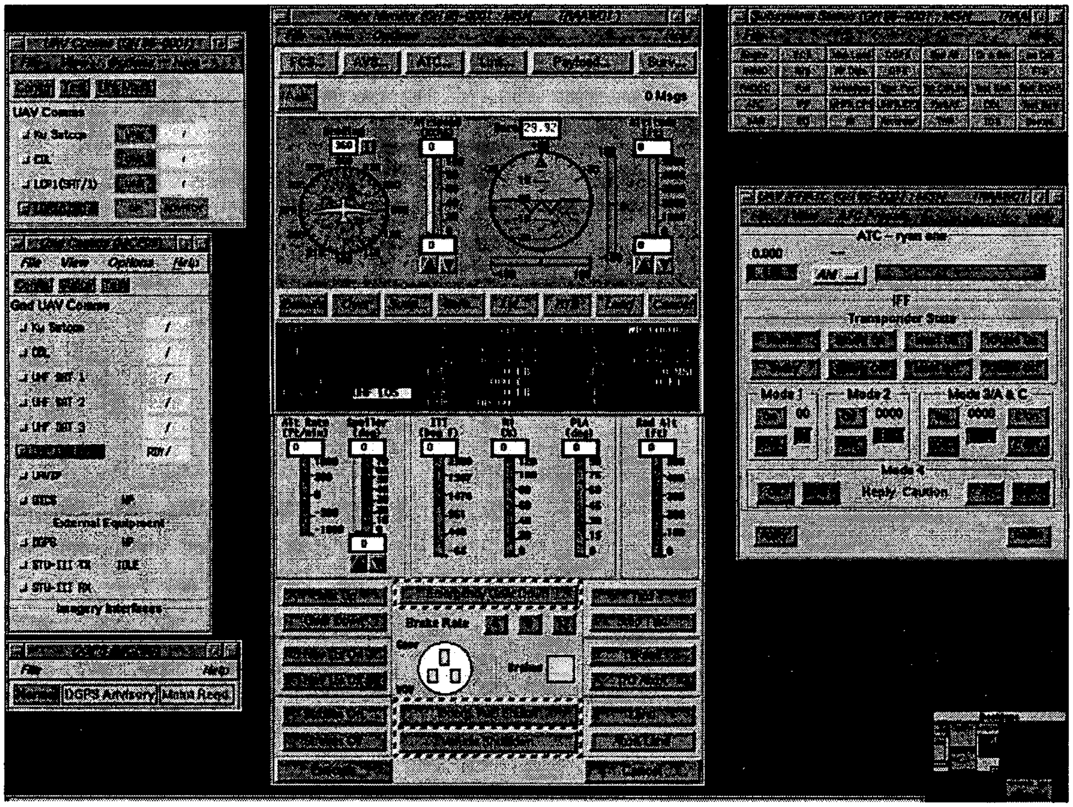
There are two general consequences of outer loop control (specification of higher level goals – e.g., navigation waypoints) associated with supervisory control systems. First, there is an increasing time lag between operator input and system response. Predictive displays are generally recommended in order to overcome the effects of this time delay [9]. Second, operators tend to become less aware of system status of performance (i.e. "out of the loop') [9]. Many methods exist to support operator mental models and system awareness, however, one important consideration is ensuring that automation behavior are highly visible to the operator [15].

The Importance of Visibility

Visibility refers not only to display salience, but also to the effort required to extract meaning from the display [16]. ROA displays must support both display salience and the easy extraction of critical information. Research indicates operators often encounter difficulties understanding automated system behavior due to automated system complexity, coupling and autonomy [16]. When operators cannot generate proper expectations of automated system performance, they often cannot direct their attention to relevant displays, or cannot properly interpret system information, resulting in poor monitoring performance. As a result, displays must guide operator attention to critical information. This is especially true given the large amounts of information that must be scanned in many supervisory control systems.

In ROAs, much of the information presented in a conventional aircraft is contained in a set of computer display screens (see figure 2 for an example ROA display screen). In addition to this information, other ROA specific information such as communication links and systems status compete for display space. As a result of the large amount of information provided in ROA displays, intelligent display technology or cueing may be required to direct operator attention to divergent information. Due to the volume of information available, some displays may include a branching menu structure, with much of the information contained out of view. Research from automated aircraft indicates that this "keyhole" effect creates difficulties retrieving important information [16]. ROA displays must provide some type of cuing strategy. Furthermore, additional study may be required to determine which information is so important that it must always be displayed – just as attitude information is so critical that standby display information is a certification requirement.

Figure 2. Example ROA display



In addition to display salience and cueing, ROA displays must also minimize the workload required to extract the relevant information (information access cost). Multi-menu displays often impose additional data management demands – the operator must not only determine what information is desired, but also where the information is located and how to access that information. Minimizing information access costs can be achieved by automatically indicating relevant information, integrating dimensions and ensuring display methods are compatible with the type of information displayed.

In summary, ROA displays must contain the information required to exercise supervisory, as opposed to manual, control. Due to the large amount of information required for ROA control, care must be taken to ensure that displays direct operator attention to relevant information and minimize the effort required to extract the information. Finally, studies must determine which information is so important that it must always be displayed, and cannot be removed or hidden in a multi-menu display.

CNS Standards and ROA HVI Requirements

Civil aviation authorities implement certification standards and regulations in order to ensure that participating aircraft meet a desired level of safety and performance. These standards contain information on system performance requirements and functional standards as well as evaluation and test procedures and requirements. While ROA's will likely have to meet the same functional and performance requirements as conventional aircraft, differences in operator roles and information requirements discussed in previous sections will require a different set of HVI standards.

Any effort to change certification standards must be undertaken within the established standards development process. For CNS systems approval in the U.S. National Airspace System, the Federal Aviation Administration (FAA) publishes various Technical Standards Orders (TSO's) and Advisory Circulars (AC's) that provide the relevant certification standards for CNS equipment. These TSO's and AC's are frequently based on standards developed by the RTCA (a broad based forum of industry, government, and user groups) which works through various Special Committees to develop an acceptable set of standards. For example, Traffic Collision Avoidance Systems (TCAS) systems are covered by TSO C-119a *TCAS II Airborne Equipment*, which is, in turn based on RTCA DO 185 *Minimum Operational Performance Standards for TCAS II Airborne Equipment.* While FAA guidance only applies to the U.S. sovereign airspace, CNS guidance is coordinated with the European Joint Aviation Authorities (JAA) through EUROCAE, the European equivalent of the RTCA.

In order to implement a set of ROA CNS standards, it is likely that the best approach will be to work within the existing RTCA Special Committee structure. Since there are many CNS standards that must be modified for ROA use, greater efficiency would be gained by consolidating ROA standards under one special committee, rather than farming the work out to a separate working group within each RTCA special committee. It is imperative that ROA operators and developers work with the FAA to begin the ROA standards development process within the existing RTCA framework.

Issues

Based on the discussions in previous sections, development of ROA standards must take into account ROA autonomy (for the specific CNS function of interest) as well as operator roles, and information needs. Since autonomy (and therefore operator roles and information requirements) varies widely between ROAs, it may not be possible to develop a single standard that would apply to all ROAs. Instead, requirements may need to be specified for several levels of autonomy. The following actions should be considered for adapting existing standards for ROAs. These actions should be repeated for each level of autonomy that is deemed acceptable for the given CNS function.

- Determine the acceptability of the given level of autonomy based on human and machine capabilities
- Identify considerations associated with the specified level of autonomy
- Identify the operator roles as a manual/supervisory controller
- Take into account general considerations associated with each operator role
- Assess the information needs of the operator
- Ensure that displays support visibility of required information

It is likely that certain levels of autonomy will not be acceptable for some CNS functions. For example, due to problems with the reliability of collision alerts, fully automated collision avoidance maneuvers may be deemed unacceptable. Alternatively, due to limited time and/or task complexity, it may be extremely difficult for the human operator to provide informed consent to proposed automated collision avoidance actions.

In addition to the considerations listed above, there are several other unique ROA issues that must also be addressed including multiple operators, multiple aircraft, reconfigurable displays, and system warnings. Each of these will be discussed briefly below.

Multiple Operators

ROAs that are capable of flying long distances or remaining airborne for long periods of time may require multiple operators. ROA HVI requirements must support control handoff between operators. If the control handoff occurs within a single facility, little change to the HVI may be necessary, however, if the handoff occurs between operators located in separate locations, procedures and displays must support the transfer of system state, automation status, and current system goals between operators.

Multiple Aircraft

Since the ROA operator is located in a ground based control center and not in the aircraft, it is possible for one operator to control more than one aircraft. This capability poses two basic questions. First, is the operation of multiple aircraft acceptable in terms of performance and safety? Second, what HVI modifications are necessary to support an acceptable level of performance? The answers to these questions may well depend on the level of vehicle autonomy, as well as operator tasks and workload levels. Further study will be necessary to provide the answers to these questions.

Reconfigurable Displays

Since many ROA displays are projected on a graphical user interface, it may be possible to reconfigure or personalize display elements to suit operator preferences. While reconfigurable displays allow the operator flexibility to adapt the displays to his/her control strategies, it may also result in display configurations that are not optimal for a given task. For example, if the caution or warning information is moved out of the operator's primary field of view, it may not result in timely operator intervention. Further research is required to determine which displays (if any) can be reconfigured without jeopardizing system performance or safety.

Warnings

Many CNS standards require that the operator be provided a variety of warning indications in the event of system degradation or loss of capability. These warning indications must be adapted to the roles and responsibilities of the operator and automated vehicle systems. For example, if response to the indicated system is delegated to the automated vehicle systems, what indications should be provided to the operator? Should the operator be informed before or after automated vehicle response? What priority order should be provided? How will the automated systems inform the operator of remaining capability? Warning issues must be assessed for each possible level of vehicle autonomy.

Conclusion

The future growth of ROA systems will depend to a large extent on ready access to civil airspace. Ready access, in turn, depends on development of ROA specific CNS standards which provide an assurance of vehicle safety, performance, and functionality. The ROA standards development process must address the critical differences between ROAs and conventional aircraft.

The primary difference between ROAs and conventional aircraft lies in the roles and information requirements of the human operator. This paper has proposed a framework for categorizing ROA autonomy and identified general HVI considerations for each level of autonomy. Given variations in autonomy between and within ROA vehicles and CNS functions, there is no one standard appropriate for all ROAs. Instead, ROA requirements must be developed for each level of autonomy.

HVI standards also depend on the information requirements of the human operator. Sheridan's model of human roles in supervisory control provides some insights into display considerations. In particular, displays must support operator's ability to develop and retain awareness of system status and goals. They must also support effective monitoring by directing attention to critical variables. Additionally, standards development must address the acceptability of a given level of autonomy and address issues such as numbers of operators and aircraft, reconfigurable displays, and warnings.

Work on ROA standards must begin immediately in order to facilitate development and spur growth in the ROA industry. We propose the development of an RTCA Special Committee to address the adaptation of a variety of existing conventional CNS standards. This paper is intended to act as spur and starting point for this important and greatly needed effort. We invite interested parties to contact the authors to further discuss and develop these ideas.

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