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Analysis of the Risks and Benefits of Flight Deck Adaptive Systems

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The objectives of this work were to identify human performance risks and benefits of adaptive systems through a systematic analysis and heuristic evaluation of adaptive system component types and characteristics. As flight deck automated systems have more access to aircraft data, sensor data, stored databases, communicated information, and real time flight crew inputs, as well as more ability to process that information in sophisticated ways to identify situational priorities and context, it is becoming more realistic for those automated systems to adapt their behavior based on context. Automated systems that can make such changes on their own are called adaptive systems. The concern here is with adaptive systems that are perceived by the pilot to behave non-deterministically even though they are technically deterministic. Based on a framework to describe the types and characteristics of adaptive system components, a risk/benefit analysis was preformed to identify potential issues. Based on this analysis, eight representative adaptive system storyboards were developed as the basis of a heuristic evaluation with pilots to validate the analysis and explore more detailed issues and potential risk mitigations. The value of this work is expected to be in suggesting adaptive system issues, risks, and guidelines that need to be considered in making design decisions and approving new adaptive systems on the flight deck.

INTRODUCTION

Implementation of Next Generation (NextGen) Air Traffic Management (ATM) concepts will require new automation and may result in substantial changes in pilot and controller roles and responsibilities. The roles and responsibilities between humans and automated systems may not be static, but may change depending upon the current context. Automated systems that have the authority to initiate changes in their own behavior are called adaptive systems. The concern here is with adaptive systems that are perceived by the user to behave non-deterministically even though they are technically deterministic. Non-deterministic systems can be defined as systems in which randomness is involved in the determination of future states of the system. It is unlikely that truly non-deterministic systems have a place on aircraft flight decks – the behavior of approved systems, by definition, has to be reliable, predictable, and reproducible. However, many adaptive systems may be perceived to behave non-deterministically; for example, they may behave according to a set of pre-defined production rules, but because they are very complex rules, the behavior appears to have an element of randomness from the perspective of the user.

As flight deck automated systems have more access to aircraft data, sensor data, stored databases, communicated information, and real time flight crew inputs, as well as more ability to process that information in sophisticated ways to identify situational priorities and context, it is becoming more realistic for those automated systems to adapt their behavior based on context. This has significant potential advantages in terms of automation performing "overhead" tasks such as information, communication, and display management based on the current and predicted situation. This can reduce pilot workload and allow pilots to focus more on primary flight tasks and less on accessing and retrieving information, configuring their displays, categorizing and prioritizing communications, and so on. Of course, realization of these benefits depends on detailed design features of the adaptive systems. Real-time adaptations also have significant potential disadvantages, such as the automation producing less predictable outputs, more opportunity for unexpected automation surprises, compromised pilot situation awareness, and cases where the automated system misunderstands calculates the situation and provides outputs that are annoying, or worse, disruptive to flight crew performance.

The objective of this work was to identify human performance risks and benefits of adaptive systems. First, adaptive system components, types and characteristics were developed. Second, a risk/benefit analysis was performed by an analyst team. Third, a heuristic evaluation was conducted with eight pilots. This evaluation served both as a validation of the previous analyses and conclusions, and as a way to explore more detailed issues and potential risk mitigations (such as design, procedural, and training concepts that can reduce adaptive system risks). This work suggested adaptive system issues and risks to be considered in making design decisions and approving new adaptive systems on the flight deck.

ADAPTIVE SYSTEMS FRAMEWORK

Adaptive Systems breaks from the traditional fixed function allocation approach by allowing the system to invoke varying levels of automation support in real time during task execution, often based on its assessment of the current context. Typically the system will turn on and turn off the adaptations, only invoking them as needed. Adaptive systems are defined here as having three key characteristics: 1) the automation is contextually aware and can actively make judgments about the state of the world and operator, 2) the automation has a range of capabilities which can be changed or adapted, and 3) the automation has the authority to initiate changes to the functions performed by the system and the human.

Adaptive Systems Architecture

Three key areas within an adaptive system architecture were identified as the most relevant for the analysis of risks and benefits: 1) *Triggers* to initiate changes in the adaptation, based on the system's knowledge of context; 2) *Decision processing*, the algorithmic process by which the system determines when and what adaptive automation to invoke; and 3) *Adaptations*, the temporary changes in automation behaviors and/or the Human-Machine Interface, designed to mitigate situations as identified by the triggers.

This paper will focus on triggers and adaptations, as these system elements are most observable to pilots, and thus most applicable to human factors risks and benefits. An analysis of the decision processing risks and benefits was conducted (for more detail, see Dorneich, Rogers, Whitlow & De Mers, 2012), but is not included here.

Types and Characteristics

Each of the major areas of an adaptive system can be instantiated in many ways. *Types* are defined as specific options within each area. For instance, trigger types include task tracking, operator state measurements, or environmental events. Likewise, examples of several types of adaptations could be task offloading, information de-cluttering, or interruptions management. Additionally, each of the three areas can be described by a unique set of characteristics that qualify their attributes. The characteristics of adaptive systems were developed based on a variety of background material, including EASA AMC 25.1302, human error categories, and known automation human factors issues (Rogers, 2011).It is these characteristics that are used to assess the risk and benefits of each type. Risk is defined as the potential of an undesirable outcome, where benefit is defined as a positive outcome or improvement in operation.

Triggers. Triggers are based on several classes of information which can be sensed, observed, or modeled to create an understanding of context, or "what is happening in the world". Five broad categories were identified (Feigh et al., in press), as illustrated in Figure 1.

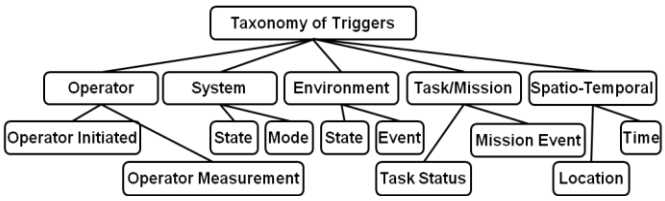

Figure 1. Taxonomy of Triggers (Feigh, et al., in press)

Estimates of the operator state are identified as the cognitive or physical states of the human operator, measured via sensors, inferred via models, or derived via interaction with the system (Scerbo, 2001). Operator-initiation is included as a trigger, since the taxonomies presented here are applicable to both adaptive and adaptable systems (Feigh, et al., in press).

Estimates of the system state may include its structure, interface, internal states, anticipated future states, rules of interaction, and its range of potential actions.

Estimates of the environment state are a representation of the world outside the immediate system and operator, and can, include environmental factors, other actors (human or automated), procedural constraints, and so on.

Estimates of the task/mission state are a representation of the tasks performed by the joint human-automation system, and include both static task representation and dynamic task tracking (Krogsaeter & Thomas, 1994).

Estimates of spatio-temporal criteria include time and location.

A set of characteristics was developed to evaluate the risks of trigger types: complexity, transparency, projectability, resolution, sensor/data reliability, state assessment reliability, pilot interaction requirements, and acceptance/trust.

Adaptations. The range of possible adaptations in adaptive systems can be broken down into four broad categories (Feigh, et al., in press), as summarized in Figure 2.

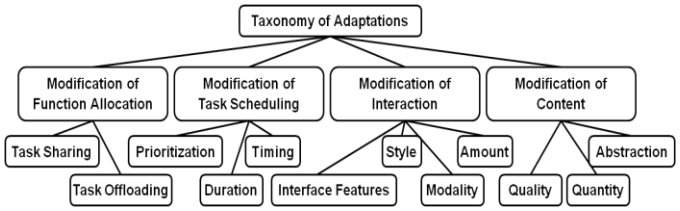

Figure 2. Taxonomy of Adaptations (Feigh, et al., in press)

The four categories include:

• *Modification of Function allocation*. A system can dynamically change who (human or machine) performs each function.

• *Modification of Interaction*. A system may be designed to dynamically change how it presents information to users.

• *Modification of Content*. A system may be designed to dynamically change what information it presents to the user, including what and how many categories of information are presented, and at what level of detail or abstraction.

• *Modification of Task Scheduling*. A system may also dynamically change when tasks are performed, including which tasks are performed first.

A set of characteristics was developed that define the attributes used to judge the risks of the adaptation types: authority change, perceived complexity, transparency, predictability, task support, pilot interaction requirements, acceptability, robustness, disruptiveness, ease of override & reversal, trust/complacency, knowledge & skill requirements, communication & coordination requirements, distraction potential, understandability, integration, novelty, interference, misleading information potential, failure modes, situation awareness impact, workload impact, usability impact, trainability impact, and error detectability.

ANALYSIS

Objectives

The objective of the analysis was to use the framework's decomposition of the different types of adaptive system triggers and adaptations, and their associated characteristics, to assess potential human performance risks and benefits relevant to adaptive system design.

Limitations

This analysis was based exclusively on expert judgment, and was intended to be a preliminary, top-down first step necessary to provide guidance for design and approval of adaptive flight deck systems and functions. The data collected was subjective, and should be considered as a first pass at quantifying the risks and benefits.

Method

The adaptive system component types and characteristics were used as matrix row and column headings, respectively, in risk and benefit scoring matrices. A team of analysts rated each combination of characteristics and types (represented by the cells in the matrix) on a scale of 1-5, (1=low, 5-high). For example, a cell in a risk matrix might compare the risk associated with perceived complexity (characteristic) for a task offloading adaptation (type). Each of three analysts individually provided ratings and narrative rationales/explanations for the ratings. Risk matrices were created for triggers and adaptations, while benefit ratings were performed for adaptations, since human performance benefits result directly from the adaptations themselves. The final risk and benefit ratings for each type-characteristic combination were based on a series of reconciliation meetings where the three raters discussed discrepant ratings, and resolved them based on discussion of rationale and examples.

Results

Triggers. Risk scores for adaptive system triggers were summed across characteristics for each type (see Figure 3).

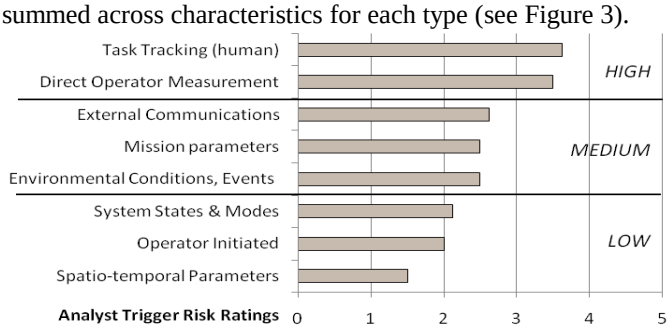

Figure 3. Trigger risk analyst ratings.

The ratings revealed three natural groupings of triggers (the groups separated by darker lines in Figure 3). The highest risk triggers included task tracking and direct measurement of operator state. The high risk of these triggers was driven by issues related to complexity, transparency, and state assessment reliability. The second group included conditions external to the humans or automation itself: communications, mission parameters and environmental conditions or events. The final grouping included automation system states and modes, operator initiation, and spatio-temporal parameters.

Adaptations. Risks were analyzed across 26 characteristics. The results for the risk analysis of the adaptations types are presented in Figure 4, where the types are ordered from highest to lowest aggregate risk.

There are three natural risk groups of adaptations, when ranked by overall risk rating, separated by dark lines in Figure 4. The top (riskiest) group all involved changes at the task level: changing the level of abstraction of information designed to support a task, offloading the entire task, changing the quantity and timing of task support, and task scheduling.

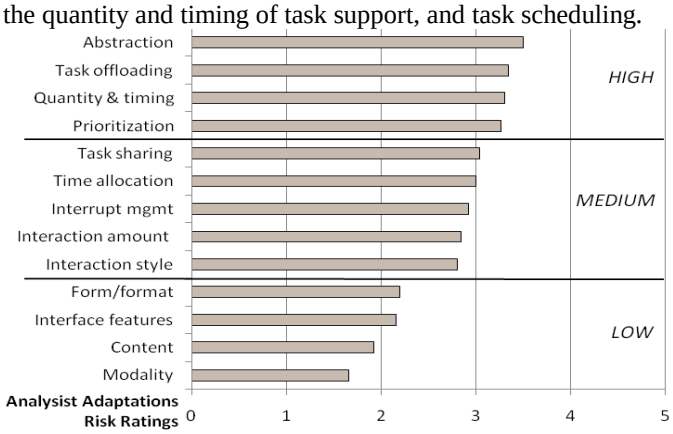

Figure 4. Adaptations risk analyst ratings.

The second group involved changes within a task: sharing of a task with automation, interrupting one task with another (or blocking another task from interrupting the current one), and changing the amount or style of interaction during task execution. Only changing the allocation of time for a task does not fit this pattern. The final group, with the lowest overall risk, included more incremental changes involving the form or format of information, changes to the pilot interface, changes to information content, and changing the modality of information.

Six characteristics were rated for adaptation benefits: Situation Awareness, Workload, Usability, Trainability, Pilot Performance, and Error Detectability (see Figure 5).

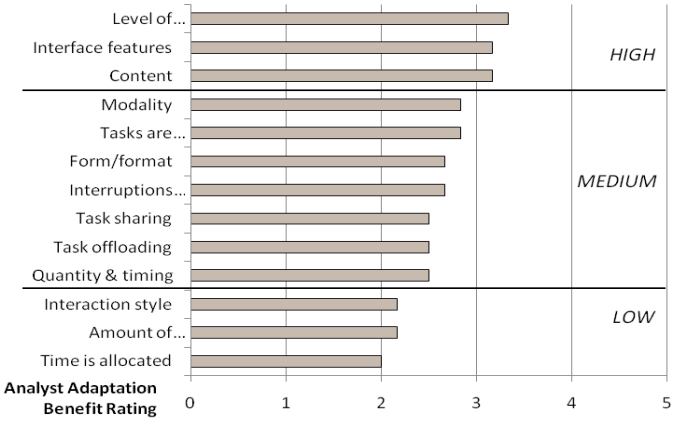

Figure 5. Adaptations benefit analyst ratings.

These were chosen from the larger set used for this exercise because they are the characteristics that reflect human performance constructs, and in the aggregate, reflect measures by which human factors benefits on the flight deck are typically described. While benefits are highly dependent on the implementation of any particular adaptation type in an actual system, ratings were developed assuming the average benefit across a range of implementation possibilities. Thus not all modality adaptations would score a “4” in situation awareness, but on average the analyst team felt that adaptations of this type would achieve this level of situation awareness.

Adaptations to the user interfaces such as abstracting or integrating information, changing the location or salience of

the information, or changing the content (e.g., de-cluttering), were judged to provide the highest benefit. Adaptations such as changing the amount of interaction required or changing the time allocated for task performance were judged to provide the lowest benefit. Interestingly, adaptations that on the surface appear to be a larger departure from current automation roles, such as managing interruptions, and offloading or sharing tasks dynamically between automation and the pilots, were judged to be of medium benefit.

HEURISTIC EVALUATION

Method

Objective. The objective of the evaluation was to collect pilot feedback to confirm, expand, and update risks and benefits ratings from the earlier analyst team assessment.

Participants. Seven male and one female pilot participated in the study; seven are currently captains and one is a lead test pilot. They averaged 56 years of age (range 43-67), averaged 8,475 (4,100-20,000) total flying hours, and averaged 2,800 (100-7,000) hours in glass cockpits. All were rated as Air Transport Pilots, four were instructors, and current aircraft type ratings ranged across general aviation, business, and commercial.

Protocol. Participants were briefed on the general types of triggers, with one or two examples for each, followed by scales on which participants rated the potential benefit and risk of each trigger type (1= very low risk, 5= very high risk). Participates were reminded to base their ratings on the general type of trigger, not the specific examples provided. After each scale, there was space for participants to explain their rating.

In order to assess the adaptation risks and benefits, eight "paper" storyboards were developed to represent notional non-deterministic automation concepts across the range of the key adaptation types, and with different combinations of risks and benefits. Participants rated risk and benefits on a scale of 1-5.

Results

Trigger Risks. Figure 6 depicts a comparison of the risk ratings produced by pilots and analysts.

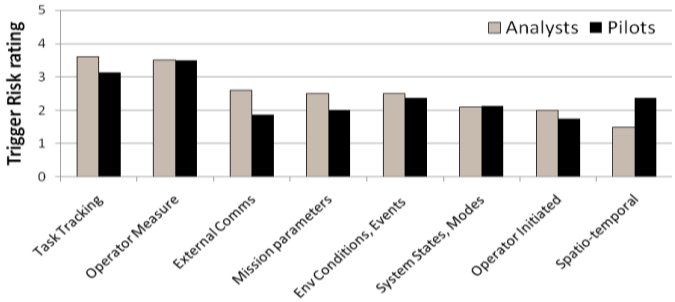

Figure 6. Trigger risk ratings for analysts and pilots.

In general the risk ratings of pilots were similar or a little lower than that of the analysts. The only trigger with a difference of more than 0.5 was the spatio-temporal trigger, where analysts rated it the least risky overall (1.8). Pilot risk ratings were driven mainly by transparency, resolution, and pilot acceptance. Six of the eight evaluation participants rated these triggers as a 2 (the other two ratings were 3 and 4). Thus overall most participants felt that the risk was very low.

Pilots rated Operator Measurement and Task Tracking as the two highest risk methods of triggering adaptations. Both of these approaches were considered to be difficult to accomplish, complex, and subject to individual variability; they may not have the levels of accuracy pilots said they needed to accept the system. Environmental and spatio-temporal triggers were rated medium risk. Environmental conditions might be a little risky if data is old or probabilistic. Spatio-temporal information will become more important as NextGen implementation matures. Lower risk triggers included system states, mission information, external communications and operator initiation. Pilots commented that these types of triggers are already in use today which could explain why they felt more comfortable with them.

Adaptation Risks. Figure 7 depicts a comparison of the risk ratings produced by pilots and analysts. Analysts rated all 13 adaptation types, while pilots rated the eight associated with the storyboards.

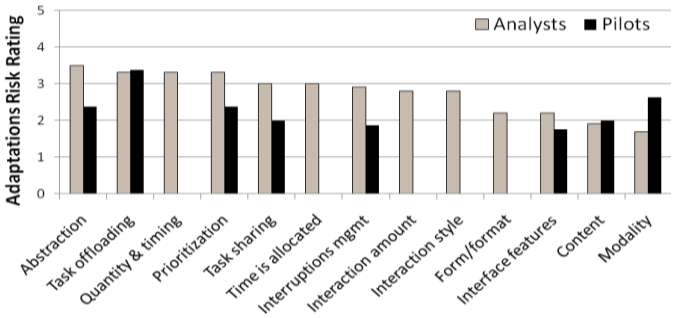

Figure 7. Adaptations risk ratings for analysts and pilots.

Overall, pilots rated the risks lower than the analysts. One explanation is that the analysts averaged their ratings for 26 characteristics for each adaptation type, while pilots gave one overall rating. It could be that some characteristics were redundant and gave more weight to the riskier characteristics, thus driving up the average risk. Pilot ratings may have been lower because they focused on near-term examples of the adaptation types, which would need to be less risky to be approved. Pilots commented that there are lots of examples of simple adaptive systems on modern airplanes, and some of the ideas presented to them are just extensions with perhaps more automation intelligence, sophistication, and complexity. While pilots felt that there will be risks with any adaptation type, it will be the implementation details of most of these concepts that will ultimately determine the risks and benefit levels.

Pilots rated Task Offloading as the riskiest adaptation type, due to concern that the adaptation takes pilots out of the decision making loop. Pilots rated the risk of sensing modality, abstraction and prioritization as medium risk, although on the low side of the middle of the risk scale. With each of these adaptations, there is the risk of the pilot missing needed information that has been abstracted away, is shifted to another modality, or is deferred. Pilots were also concerned that modality changes from visual to auditory could distract them or interfere with other auditory information. The lowest risk group of adaptations included task sharing, information

content, interruption management, and interface features. Since none of these adaptations took control out of the hands of pilots, they rated the risk as lower than adaptations that do.

Adaptation Benefits. Figure 8 depicts a comparison of the benefit ratings produced by pilots and analysts.

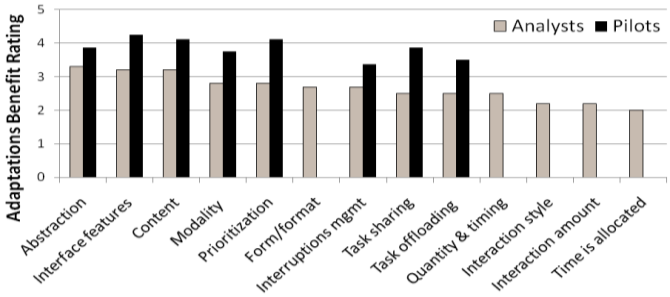

Figure 8. Adaptations benefit ratings for analysts and pilots.

Interface features, information content, and prioritization were all rated by pilots above 4 on a 5 point scale. All of these adaptations helps pilots manage situations, and were considered especially beneficial during abnormal operations by helping pilots with the executive function of managing their tasks and the displays that support them. Task sharing, abstraction, and sensing modality formed the middle group of adaptation types. Both abstraction and sensing modality have the ability to direct attention to information, allowing pilots to maintain an appropriate level of situation awareness. While still rated well, benefits were seen as lower for task offloading and interruption management. Pilots felt that these adaptations types have to be simple to be effective, thereby reducing the scope of benefit to overall system performance.

In every instance, pilot ratings of benefits of the adaptations they rated were higher than the analysts' ratings. In general, pilots were very positive about the storyboards they reviewed as part of the evaluation. If adaptive automation could function as a third pilot or co-pilot and anticipate needs, then this would be a great benefit to flight crews. It would be like a good co-pilot who asks you if you want something done in a particular situation where you would normally do it. Pilots generally liked the adaptive nature of the system, although there was skepticism about the benefit of adaptive systems over good full time, well designed automation concepts.

DISCUSSION

Pilots expressed concern about the impact of advanced automation on pilot roles and responsibilities. For example, in normal operations there is almost no manual flying by pilots. It is the other tasks that "keep it interesting and fun." So if more of these other tasks are automated, there is less for the pilots to do. Adaptive systems that potentially only offer more automation when it is needed, allow the pilot to keep control of more engaging tasks during most normal operations.

Several pilots commented on the adaptive nature of the concepts presented. They asked, if the automation does their tasks well, why not have the automation do it all the time? Further, as the analysis and evaluation suggested, there are costs (realized risks) with every adaptation. It is the function of the processing to decide when the benefits of the automated intervention outweigh the costs. That calculation changes depending on the particulars of the situation, as defined by the triggers. Thus the heart of a good adaptive system is one where the complex trade-offs between the costs and benefits under various conditions are factored into system behavior.

The analysis and evaluation evaluated the potential costs and benefits across a range of triggers and adaptations types. Overall, pilots rated adaptations that changed information displays as lower risk than adaptations that potentially affected the direct control of the aircraft. For adaptations that affect the aircraft, pilots felt that the adaptive system should always ask rather than just take control.

From a pilot perspective, the complexity of the adaptive system drives the perception of whether it is "non-deterministic." When there is only one trigger (and one simple "if-then" rule to turn on/off an adaptation), pilots felt that these systems were just part of the design (and thus not adaptive). They cited many examples of such systems on today's flight decks. Pilots like adaptive system concepts best when they are simple and deterministic. The more complicated they become; the more risky they felt the systems would be. One pilot speculated that once the number of triggering conditions approached five or more, pilots would lose the ability to understand what the system is doing, and what it will do next. At that point the system would be perceived as "non-deterministic," which he equated to the loss of pilot awareness of the automation. However, pilots felt that is the "system got it right" then they were less concerned with transparency.

Pilots clearly saw the potential benefits of increasingly active automation that could anticipate pilot needs and automatically trigger changes in automated support. Those benefits, however, will only be realized when carefully weighed against the costs.

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