BBN Report No. 8436

Single Pilot Commercial Aircraft Operation

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November 2005

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Table of Contents

1. Introduction

Preparing the way for single pilot commercial aircraft operation that can achieve the level of safety and operating efficiency of today's two person aircrews presents significant challenges. As we design single pilot operations, we will need to keep in mind that today's two-person aircrew with well-established roles of captain and first officer and a pilot-flying and pilot-not-flying task breakdown remain vulnerable to sequences of errors that lead to incidents and accidents (Klinect, Wilhelm, & Helmreich, 1999). As we think about employing new technologies, it is also important to remember that the introduction of new technologies and procedures designed to increase safety and efficiency can lead to new forms of error (Weiner & Curry, 1980; Norman, 1990; Billings, 1997).

In this short-term study, it has been necessary to restrict ourselves to a very disciplined approach. We center this approach on cognitive work analysis and the use of human performance models for aircrews to support the initial evaluation of proposed procedures. First, we endeavor to better understand how two-person crews operate today. The cognitive work analysis to contribute to this understanding has not been done at this point. What we do have is a cognitive task analysis for approach, landing, and taxi operations (Keller & Leiden, 2002) and human performance models for two-person crews and controllers for approach, tower, and ground control. The task analysis, the model scenarios, and further work with domain experts will form the basis for the recommended cognitive work analysis. The human performance models for the captain and first officer will form the basis for the models for the single pilot and, as we shall see, the automation as well.

Given the cognitive task analysis and the models and absent the cognitive work analysis, we have prepared some initial thoughts on how single pilot operations for commercial aircraft might be configured. A short list of relevant technologies is identified that is viewed as having a significant role in single pilot operations. We then suggest how these technologies might be used in isolation and in combination to support the development of single pilot operating procedures and requirements for systems to support these operations.

This report consists of four sections. We begin in Section 2 by describing the methodological steps based on cognitive work analysis and human performance modeling that would lead to initial recommendations for operating procedures for single pilot operations. We then present the main findings of the study identifying the technologies identified as potential contributors to single pilot operations, an approach to single pilot operations based on these technologies, and a software framework for implementation of the supporting automation. Section 3, a section adapted from a previous report (Deutsch & Pew, 2004a), reviews aircrew vulnerabilities to error as identified in selected NTSB accident reports. Section 4 provides recommendations on the next steps to be taken in developing single pilot operating procedures. Lastly, Appendix A, also adapted from the previous report, describes the operations of the human performance models that emulate aircrew and controller procedures and may be adapted to support the evaluation of new procedures developed for single pilot operations.

2. Single Pilot Commercial Aircraft Operation

In the longer term, the development of single pilot procedures for commercial aircraft operations will be a formal FAA-governed process. We advocate an additional step in the preliminary stages of the procedure development methodology that makes use of human performance modeling. The additional step is expected to facilitate a faster and more thorough evaluation of early ideas for single pilot procedures. The model-based development, evaluation, and selection process for procedures for single pilot operations is anticipated to speed the overall process of procedure development and validation by producing more mature candidate procedures earlier in the development process.

In this section, we outline proposed methodological steps in single-pilot procedure development based on cognitive work analysis and the use of human performance modeling. The scope of the current study did not permit us to pursue all elements of the methodology that we advocate. In particular, we did not have the resources required for the necessary cognitive work analysis or model-based procedure evaluation that is discussed below. We did identify technologies that we believe have an important role to play in single pilot operations. Having identified technologies that might be employed, we then suggest an approach to single pilot operations in which the technologies are assembled to emulate, to the extent possible, the role of the pilot-not-flying. In doing so, we suggest that the well-established two-person aircrew roles of pilot-flying and pilot-not-flying provide a model for single pilot operation supported by automation. It will be necessary to demonstrate that the approach that is reliant on the selected technologies yields an adequate level of safety of flight.

2.1. Work Analysis, Performance Modeling, and Procedure Development

As we begin to think about moving from two person aircrews to single pilot operations for selected commercial flights we have started by looking carefully at current two person operations. Over the past several years, we have been involved in a series of NASA Ames sponsored research projects that have involved the modeling of aircrew and controller operations. In most cases, the modeled scenarios have focused on approach, landing, and taxi operations for two person aircrews (Deutsch & Pew, 2001; 2002a; 2002b; 2003; 2004a, 2004b; 2004c; Deutsch, 2005). A current study focuses rather on en route controller operations and provides insight into procedure for the use of new technologies at the controller workplace and the use of data link to support communications. These typically high workload activities have served us well in taking an initial look at ideas for equipment and procedures to support single pilot operations.

A cognitive task analysis (Keller & Leiden, 2002) provided an important input to the model building process for approach and landing procedures. For each of the research efforts, the task analysis was supplemented by additional materials on airport and airspace configurations, baseline and enhanced flight deck equipment (e.g., cockpit navigation displays to increase safety and efficiency of surface operations, a synthetic vision system), and aircrew and controller procedures and operations. In addition, we were provided with detailed human subject data from relevant human-in-the-loop simulation studies (Hooey & Foyle, 2001; Goodman, Hooey, Foyle, & Wilson, 2003). The cognitive task analysis and the supplementary data provided an excellent basis for the development of human performance models for the aircrews and the controllers.

The current captain and first officer human performance models readily negotiate approach, landing, and taxi operations at the O'Hare, Santa Barbara, or Charlotte airports using either ILS or RNAV approaches; they make use of the SVS when the flight deck is so equipped; and, have a limited ability to address weather cell issues as seen in the Charlotte approach. The O'Hare and Santa Barbara approaches were flown with the captain as pilot-flying; the Charlotte approach was flown with the first officer as pilot-flying. The models are *generative* in the sense that given their basic operational knowledge in the form of goals and procedures, information sources such as approach plates and airport diagrams that they were able to draw on, and the sequence of approach, tower, and ground controllers with whom to interact, the human performance models were able to realistically complete the approach, landing, and taxi operations at the various airports in a human-like manner.

The models provide working examples of a captain and first officer interacting with a sequence of controllers to complete landing operations under varying circumstances. As such, they provide a particular partitioning of the essential tasks between captain and first officer during these phases of flight. In looking at single pilot operation, we began our analysis from this partitioning. The models are, in effect, a working extension of the cognitive task analysis. They represent the three-way partitioning of the work to be accomplished among captain, first officer, and the supporting systems. In proposing procedures for single pilot operation, we are looking at how to move to a two-way partitioning of the work between a single pilot and supporting systems, while also looking at the potential for redefining some of that work particularly as new technologies are employed.

From a methodological perspective, we advocate a continuation of the current study consisting of two main elements: a cognitive work analysis as the basis for the development of single pilot procedures and the use of a fast-time scenario trials using a single pilot human performance model for the initial evaluation of proposed procedures. Cognitive task analysis traditionally examines the workplace and procedures through which skilled practitioners accomplish their tasks. Cognitive *work* analysis (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999) steps back from the organization of the tasks as currently defined to look at the underlying work and how it is *actually* being accomplished (Naikar, Moylan, & Pearce, in press). In Degani and Wiener's (1994) terms, cognitive work analysis develops a detailed view of aircrew *practices* on the flight deck. With the cognitive work analysis in hand, we would then be able to review the underlying work, propose modifications where appropriate, and subsequently carry the study forward to look at a revised partitioning of the work, this time between a single pilot and supporting systems that may employ selected new technologies. Based on the cognitive work analysis, new operating procedures would be developed for single pilot operation.

With the new proposed procedures in hand, the second step would be to explore this new two-way partition of the work by extending the current modeling environment. The human performance model for the captain would be refined to become the model for the single pilot. With the selection of the new technologies to be employed, the flight deck model would be extended to reflect the capabilities of the automation to support single pilot operations. We would also examine the potential for changes in controller operations. The models for controller workplaces, procedures, and models for the controllers themselves would be revised as necessary. The new modeling environment would also include a first implementation of the proposed automation; hence, it would provide a first look at how the supporting automation might be made operational. Human performance models for the single pilot and controllers would provide a first look at the operational performance of the proposed procedures and automation for single pilot operations.

Given the new equipment and the new single pilot and controller procedures, the next step would be scenario development. A series of scenarios can readily be built based on the current approach scenarios to O'Hare, Charlotte, and Santa Barbara airports. Once we have a reasonable level of successful execution on the initial scenarios we would want to explore the effects of increased workload. One approach to increasing single pilot workload would be to embed the target aircraft in a denser flow of approach aircraft. A second tactic would be to add workload by imposing weather related events. Weather cell threats as seen in the Charlotte scenario are representative of flying conditions in the southeast in summer that can increase pilot workload. The scenarios from previous work provide a good base from which a series of progressively challenging trials can be constructed.

In summary, the path from cognitive work analysis to human performance model trials provides a constructive means to develop and test a range of approaches to single pilot commercial aircraft operations. The process beginning with a cognitive work analysis is an iterative one. A first goal is to select and employ useful technologies and develop single pilot and controller procedures to readily handle near nominal conditions. Increasing trial difficulty would uncover problems leading to subsequent iterations through the process. Some problems may well not be suitably addressed through the use of human performance model based trials, but may require human-in-the-loop trials to address performance issues not adequately addressed in the models.

The issue of human error is more complicated. Flight deck errors do occur and can combine into chains that lead to incidents and accidents (Klinect et al., 1999). Moreover, new technologies and new procedures can introduce new forms of error (Weiner & Curry, 1980; Norman, 1990; Billings, 1997). Models developed as part of the NASA Human Error Modeling element within the Aviation Safety Program (Foyle, Hooey, Byrne, Corker, Deutsch, Lebiere, Leiden, & Wickens, 2005) demonstrated some success in using human performance models to gain new insight into the sources of human error. As we develop procedures for single pilot operations, some effort should be devoted to probing the models to identify potential sources of human error (Deutsch & Pew, 2002; 2004a; Deutsch, 2005) in proposed single pilot operating procedures.

2.2. Technologies

As we examine potential paths to single pilot commercial aircraft operation, it is natural to point to new technologies that have the potential to contribute to the success in these operations. Data link will replace much of today's voice-based communication between aircrews and controllers. Taxiway navigations aids have been shown to have the potential to reduce taxiway navigation errors. Speech recognition and natural language understanding and agent-based system technologies can potentially play an important role in assembling cockpit automation and procedures for single pilot operations.

2.2.1 Data link

The handling of communication with air traffic control is typically a key task of the pilot-not-flying. Augmenting or replacing the traditional voice communication link by data link places new demands on the aircrew for head down time. The pilot-not-flying must process the messages and communicate their content to the pilot-flying. While data link is a technology that has the potential to serve the two-person aircrew well, in single pilot operation, absent the pilot-not-flying, the impact of the use of data link with its demands for additional head down time becomes an issue to be addressed.

2.2.2 Taxiway Navigation Aids

The use of the NASA Ames Taxiway Navigation and Situation Awareness (T-NASA) system was explored in a series of human-in-the-loop simulation studies and found to significantly reduce the incidence of navigation errors in surface operations (Hooey, Foyle, Andre, & Parke, 2000; Andre, Hooey, Foyle, & McCann, 1998; McCann, Hooey, Parke, Foyle, & Kanki, 1998). The system includes a head-up display (HUD) and a head-down electronic moving map (EMM) display operating in combination with a data link system. In the simulation study where both the HUD and EMM were used, the system was been shown to lead to increased taxi speeds and to virtually eliminate navigation errors (Hooey et al., 2000). Some variation of the T-NASA system, perhaps using the HUD, seems well suited to supporting single pilot taxi operations.

2.2.3 Speech Recognition and Natural Language Understanding

Voice communication is a key element supporting aircrew teamwork. There are numerous points during an approach and landing, and more generally across all flight phases, at which a pilot-flying uses voice communication to request pilot-not-flying actions which are then cross-checked. Hence, it is a small step to think in terms of a single pilot using speech to coordinate flight deck operations with an automated agent. In fact, current two-person aircrew procedures provide an excellent model of how the dialogue between a single pilot and an automated agent might proceed. At the same time, one needs to be mindful of just how poorly many of the voicedbased systems that we encounter daily behave. We have looked at the use of speech recognition, natural language understanding, and text-to-speech systems as element of the proposed automation. It will also necessary to ask how we will proceed if we do not use these technologies—for the present, we have not examined this path.

Speech recognition, natural language understanding, and text-to-speech are maturing technologies that might well enable a single pilot to manage the elements of the automation employed to support single pilot operations. Systems such as BBN's Byblos can provide large-vocabulary, speaker-independent continuous speech recognition in real-time operating on off-the-shelf hardware. In contrasting speaker independent- with speaker-trained systems, speaker independence has proven more robust across the day-to-day variations of an individual speaker. Current research programs continue to advance the state of speech recognition technology and deliver significant improvements in recognition accuracy for speech in different environments. Dialog design using statistical speech recognition and natural language understanding enables "mixed initiative" dialogs enabling the user to speak more conversationally. While precise syntax and content is encouraged in flight deck communication, it cannot always be guaranteed and robustness in the face of variation provides needed backup.

Our purpose here is to explore the use of speech recognition and natural language understanding as a technology to assist the transition to single pilot operations. Safety and reliability are concerns that must be carefully evaluated before such systems are deployed on the flight deck, but a thorough investigation of these concerns is beyond of scope in the current study. For now, we first point out that the flight deck noise environment must be addressed—the feasibility of the use of close talking or noise canceling microphone is a first step to be explored. Secondly, speech recognition should be employed in a multi-modal user environment—that is, there should be a non-speech mode through which to cancel a speech-initiated action due to a misinterpreted command or simply the need to retract the commanded action.[1]

2.2.4 Agent-based Software

The Distributed Operator Model Architecture[2] (D-OMAR) provided the software environment for building the human performance models for the O'Hare taxi scenarios, the SVS studies at SBA, and the modeling of the 1994 windshear accident at Charlotte. Like real aircrews, the models have proactive goals covering the primary aircrew functions of aviate, navigate, and communicate. Their goals are expressed as plans that break down into sub-goals with procedures that execute aircrew actions for the approach, landing, and taxi operations that the models conduct. The aircrews must also respond to impinging events. The models' response to these events is to govern their actions by channeling their responses through goals that manage these, for the most part, anticipated events. A cognitive task analysis (Keller & Leiden, 2002) led to the development of the goals and procedures that execute the tasks that drive the captain, first officer, and controller human performance model behaviors in the scenarios.

As we think about single pilot commercial aircraft operation, we are revising the cognitive task analysis to reapportion the tasks of the captain and first officer to those shared by a single pilot and supporting automation. The representation of the work to be accomplished by the pilot and the automation eventually will be expressed in terms of procedures executed by the single pilot and supported by the automation. At this point in the development, the work to be accomplished by the single pilot is derived from the pilot-flying tasks, the work to be

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[1] The authors wish to thank Pat Peterson for these insights with respect to deploying speech technology on the flight deck.

[2] Information on D-OMAR is available at the web site omar.bbn.com. Java and Lisp versions of D-OMAR are available as OpenSource at the site. The Lisp version of D-OMAR was used for the human performance modeling discussed in this report.

accomplished by the automation, derived from the pilot-not-flying procedures are similarly expressed in human terms. On the automation side, we are left with work defined in human-like terms and a difficult transition into software implementation.

In essence, object-oriented software development is founded on real-world like, but software-oriented object definitions and processes implemented as methods, each realizing minute steps in a larger process. The large-scale structure of the software, to the extent that it exists, is in difficult to decipher documentation. An approach to extending the software foundations for implementing the automation, and open it to inspection and discussion, is to take advantage of the software tools that have been implemented to construct human performance models. The software tools that implement the automation might be much like the software tools from which the human performance models are built. The same software tools that support the mix of proactive and reactive behaviors in human performance models can form the basis for *agent-based* system development that implements the automation to support single pilot operations. The agent-based system capabilities to appropriately interleave the demands of multiple concurrent tasks typically exist as software extensions built on an object-oriented substrate.

The cognitive work analysis that defines today's pilot-not-flying tasks can become the basis for the requirements to be placed on the automation. These requirements can readily become the specification for an automation implementation based on agent-based software technology. The cognitive work analysis expressed as the prioritization and interleaving of proactive and reactive tasks can be directly and readily expressed as the operations of an agent or agents in an agent-based system.

One of the striking things that has happened in moving to an agent-based software implementation is that the dialogue between the cognitive engineers doing the cognitive work analysis, the users for the system being developed, and the software engineers developing the system has suddenly opened up. This was very much in evidence in developing a weather management system for the Air Force (Scott, Roth, Deutsch, Malchiodi, Kazmierczak, Eggleston, Kuper, & Whitaker, 2005). While an object-oriented implementation has been the private domain of the software engineers, software implement using agent technology becomes something in which the entire team can be conversant. Rather than being expressed in the minutia of objects and methods meaningful only to software engineers, the software is implemented as a realization of the work analysis in terms that all parties can readily understand. The structure of the software to be implemented is expressed much like the procedures an aircrew might execute. An agent-based system approach will typically employ object-oriented programming techniques. In the agent-based implementation, the agent layer also serves as an essentially descriptive layer. It provides a software language layer that is readily understandable by the entire team and about which everyone can readily converse and exchange ideas—the software design and implementation for the automation ceases to be a black box available only to implementers.

2.3. Procedures for Single Pilot Operations

The move from a two-person flight crew to single pilot operation for selected commercial aircraft suggests a major redesign of flight deck procedures. Pursuing an alternate tack, we put forward a minimalist approach to redesign by looking at how close to current two person procedures we can remain while eliminating the second pilot. The move also suggests a rethinking of the philosophy and policies with respect to procedures (Degani & Weiner, 1994). Pressed for time in the immediate study, we have set aside philosophy and policy to pursue a depth first approach examining a particular path by which to structure procedures for single pilot operations. Our expectation is that at a later date there will be adequate time to establish a philosophy with policies for single pilot operations and explore a broader range of approaches to single pilot procedure development. The approach that we put forward here might then be reevaluated within that larger framework.

In establishing procedures for single pilot operation, the captain will become the single pilot as the pilot-flying and the responsibilities of the pilot-not-flying, tasks that may be executed either by the captain or first officer in a two-person aircrew, must be reallocated for single pilot operation. At the top level, the pilot-not-flying supports pilot-flying operations, handles communication with air traffic controllers, and provides a vital second flight deck perspective checking operations to prevent and mitigate error and thereby insure safety of flight. The traditional tasks that are shared by the captain and first officer are aviate, navigate, and communicate. Insuring safe operation is implicit in the traditional task list; here we call it out explicitly as deserving of special attention in moving to single pilot operations.

We the present we have pursued a single approach in examining strategies for single pilot operations. The basic approach discussed below can be characterized as employing voice technology to enable the automation to emulate many of the capabilities provided by the pilot-not-flying in today's two-person aircrew. We are using today's two-persons flight deck procedures as a grounded model for how the single pilot and the automation are to operate. An important question that will need to be answered is can the proposed automation be made sufficiently robust in its emulation of the pilot-not-flying to meet the stringent requirements for safety of flight.

2.3.1 The Role for Voice Technology

Appendix A provides an outline of approach, landing, and taxi operations as we have come to understand them. The human performance models for the captain and first officer closely follow the procedures outlined in that section and successfully execute the tasks required by the simulation environment. The development of the procedures was based on the cognitive task analysis (Keller & Leiden, 2002) that was provided as input to previous model building studies. We start from the perspective of captain as pilot-flying and first-officer as pilot-not-flying. As we begin to think about single pilot operations, the captain becomes the single pilot and it is the pilot-not-flying tasks that must be redesigned and reallocated between the single pilot and supporting automation.

In looking at the pilot-not-flying role, we see that many of the essential operations are in service of verbal requests made by the captain, for example, adjusting the flaps as they proceed with the approach and lowering the landing gear. These are operations that a single pilot may well execute; on the other hand, voice activation offers a potential alternative approach emulating operations of today's two-person aircrews. A single pilot could then speak to the automation, much as he or she converses with the pilot-not-flying, to accomplish these operational steps. Manual execution of these settings would then serve as a backup to voice activation.

Looked at more generally, pilot-not-flying actions in support of the pilot-flying are a mix of proactive behaviors initiated by the pilot-not-flying and reactive behaviors in response to the pilot-flying or the air traffic controller. The setting of flaps and lowering of the landing gear cited above are reactive responses on the part of the pilot-not-flying in response to pilot-flying requests. Self initiated callouts for localizer and glides slope capture, altitude (typically at 1000 feet AGL, 500 feet AGL, approaching decision height, and at 100 feet AGL), and groundspeed after landing are proactive actions on the part of the pilot-not-flying. These are operations are well within the capabilities of automation that includes speech recognition, language understanding, and text-to-speech subsystems.

We have been frustrated by encounters will badly designed voice-based systems. A multi-modal call center director dialogue provides an example of a well-paced speech recognition dialogue through which the automation connects a telephone caller with his or her desired party. This system, well received by users, provides a starting point in thinking about how such a voice system might be deployed on the flight deck. Upon dialing the call director with the intent to reach Steve Deutsch, the dialogue proceeds as follows:

System: Name please, <beep>

Caller: Steve Deutsch

System: Thank you, Ringing Steve Deutsch, to cancel press star

Barring the pressing of the “star” button, the system proceeds with the call as announced. In the case that the “star” button is pressed to cancel the call, the system provides the opportunity to try again by responding as follows:

System: Canceled, name please, <beep>

Where upon, the dialogue would continue as before.

On the flight deck the dialogue might be simply rendered as:

Pilot: <push to talk> Flaps 15

Automation: Flaps 15 <pause> <set flaps 15>

The need for the automation to prompt the action to initiate the canceling of the action should be evaluated. The duration of the pause between the automation response of "Flaps 15" and the setting of the flaps will need to be determined. The call director example uses the phrase "press star to cancel" both to prompt the user on how to cancel the request and to fill the time between acknowledging the request and executing the request—the prompt may not be needed. Much like on the flight deck today, the single pilot would participate in two conversations, one with the automation supporting pilot-not-flying operations and one with the air traffic controller—two separate "push to talk" communication paths.

Requiring push-to-talk for the conversation with the flight deck automation needs further attention. Simply speaking to the flight deck automation would emulate today’s conversation with the pilot-not-flying, yet the cockpit environment may make this impossible. The workload associated with this extra task step of push-to-talk needs to be addressed. If the landing gear is lowered by the dialog sequence <push-to-talk> <"lower landing gear"> is that actually less workload than simply executing the 'lower-landing-gear-task’ manually. Furthermore, since there will now be two push-to-talk paths, there is the possibility to select the wrong one for the subsequent message—a new error mode. We think suitable designs to address these problems can be worked out, but it is an area for further study.

The reactive and proactive voice-based operations are relatively simple in that, baring misunderstanding or error, a transaction is completed in a single exchange. The execution of checklists represents an extended exchange between a pilot-flying and a pilot-not-flying. Checklists are much studied (e.g., Degani & Wiener, 1990; 1993; Turner & Huntley, 1991) and have a long history as sources of error (see Section 3.1). Once again, automated speech and voice offer a means to capture the sense of two-person operations. The pilot would initiate execution of a checklist with the automation filling the role of the pilot-not-flying in stepping through the checklist items. Nominal execution of a checklist can be expected to be straightforward; it is the many alternate paths that can develop that will present implementation problems. Adding automation for checklist processing in a two pilot crew environment has proved to be very difficult. Here again, the two person procedures with one person replaced by automation may provide a model making it easier to proceed. One concern among the several to be investigated is the use of gesture that flight crews readily make use of to direct attention during checklist processing. There will need to be alternate approaches by which the automation achieves this level of communication with respect to visual attention in checklist processing and crosschecking.

Access to emergency and abnormal checklists is a further service that a voice-based system may be able to provide the single pilot. The foundation for this capability is in the work being done in question answering using textual sources. Typical approaches are based on a hybrid of information extraction, natural language parsing, and information retrieval. Hence, there is the potential for voice-activated access to the relevant checklist followed by checklist processing. In emergency or abnormal situations, a more extensive capability might provide answers to a single pilot's questions drawing on an onboard maintenance or emergency situation database.

2.3.2 Data Link Operations

Voice technology can potentially play a central role in supporting the use of data link on the single pilot flight deck. While the required head down time to read and process data link messages does not present a problem for the pilot-not-flying, the same demands on the single pilot may be very difficult to accommodate under high workload conditions. Once again, the automation could be asked to take on the role of the pilot-not-flying by voicing the data link messages, conveying acknowledgements, and supporting the execution and cross-checking of required actions. If the automation is to take on the task of verbal communication of data link messages, the automation will need to be sensitive to the multiple tasks that it may have in process as well as the other demands on the single pilot.

2.3.3 Multitasking in Agent-based Software

A consistent theme in this discussion has been the use of voice technology to support single pilot operations. In this approach, pilot-not-flying procedures have formed the basis for establishing the support to be provided by the automation. Taken together, the individual tasks to be performed by the automation can be viewed as the procedures of an agent, in this case a software agent. Just as the pilot-not-flying must manage multiple, often concurrent demands, the software agent will be faced with very similar demands. The agent will need to manage proactive and reactively grounded tasks involving exchanges with the single pilot and there are data link based interactions with the pilot and air traffic controllers that must be interleaved. Just as the pilot-not-flying is multitasking, the automation utilizing voice technology must similarly be capable of multiple task management. Proactive callouts, responses to pilot requests, and controller data link demands must be interleaved in a manner sensitive to the immediate workload and capabilities of the single pilot.

These are just the issues that have been faced in building human performance models for aircrews. Particularly relevant are the models for the crewmember playing the pilot-not-flying role. The human performance model for the pilot-not-flying is executing the tasks that we would like the automation software to take over. Software technology that has supported the development of human performance models can serve as a model for an agent-based system that could implement the automation to support single pilot operations using voice technology.

The level of capability that can be achieved by a software agent and the acceptance by a single pilot of the voice communication with such an agent will need to be investigated. The shared understanding and communication of intent will play an important role (Funk & Miller, 2001) in agent capability. Late in the approach and landing sequence under difficult weather conditions, the pilot-flying might be forced to abort the landing and announce, "going around, gear up, flaps 15." The pilot-not-flying would then raise the landing and set the flaps, in effect telling the automation, "gear up, flaps 15." For the proposed approach to single pilot operation, the communication of intent to the agent, "going around," can play a critical role in achieving the necessary level of safety of flight. From the perspective of speech recognition and language understanding, having heard "going around," "gear up, flaps 15" will then simply match the agent's expectations. Open questions include: When intent is not communicated to the automation, what is the backup capability required on the part of the software agent to assure safety of flight? Will the provision to quickly countermand a misunderstood command suffice? Communication of intent will lead to more robust agent capabilities, but backup must be in place when intent is not communicated.

3. Observations Derived from a Review of Selected NTSB Reports

Thinking about and conducting experiments to probe the vulnerabilities to error of new, or for that matter current procedures have proven to be very difficult. Skilled aircrews executing robust procedures commit errors that, on the surface, can be hard to understand. As we construct approaches to single pilot operations, we need continually probe the proposed procedures to identify vulnerabilities to errors that can potentially lead to accidents. NTSB accident reports provide insight into the range of human vulnerabilities—more needs to be done to better understand the sources of those vulnerabilities.

In a previous study, we explored the use human performance models as an approach to better understanding the sources for aircrew decision-making errors (Deutsch & Pew, 2004a; Deutsch, 2005). In the course of that study, Orasanu and colleagues identified a series of NTSB accident reports that provided detailed information on events leading to the accidents (Orasanu & Davison, 1998; Orasanu & Martin, 1998; Orasanu, Martin, Davison, 1998). To narrow the list of NTSB reports to be reviewed we elected to focus on those for which the accident occurred during approach and landing and in which plan continuation errors (Orasanu, Martin, & Davison, 1998) were determined to play a role. We review the range of errors identified in the previous study because of their potential to alert us to possible error sources in the procedures that we seek to define for single pilot operations.

There have been a number of summary reviews of the role of aircrews in accidents involving U. S. carriers (e.g., NTSB, 1994b; Wiegmann & Shappell, 2003). Our purposes within the previous study were more limited. We reviewed the reports of a small number of accidents on approach and landing to gain a better understanding of the multiple factors that come into play and that in combination lead to accidents. In particular, in pursuing the review we were looking for the elements contributing to errors in aircrew decision-making that were uncaught and combined to provide the framework in which an accident occurred.

In this section, we highlight the factors identified in the review that are representative of issues that are important in better understanding aircrew error. These are issues that, as we develop procedures for single pilot operations, provide insight into how human error can intrude in what are nominally robust procedures. They relate principally to lapses in the execution of standard procedures, failures of aircraft systems to successfully alert an aircrew to explicit problems, and psychological phenomenon related to human error. In several instances, multiple error types occurred within a single accident scenario.

The list of NTSB accidents reports that were included in the earlier review are listed here in chronological order:

- NTSB/AAR-86//05, Crash while Approaching to Land, Delta Air Lines, Flight 191, L-1011-385-1, N726DA, Dallas/Fort Worth International Airport, Texas, August 2, 1985
- NTSB/AAR-94/04, Uncontrolled Collision with Terrain, American International Airways Flight 808, DC-8-61, N814CK, U. S. Naval Air Station, Guantanamo Bay, Cuba, August 18, 1993

- NTSB/AAR-95/03, Flight into Terrain during Missed Approach, USAir Flight1016, DC-9-31, N954VJ, Charlotte, North Carolina, July 2, 1994
- NTSB/AAR-96/05, Collision with Trees on Final Approach, American Airlines Flight 1572, MD-83, N566AA, East Granby, Connecticut, November 12, 1995
- Crash on Approach, American Airlines Flight 965, Boeing 757, N651AA, Buga (near Cali), Columbia, December 20, 1995
- NTSB/AAR-97/01, Wheels-up Landing, Continental Airlines Flight 1943, Douglas DC-9 N10556, Houston, Texas, February 19, 1996
- NTSB/AAR-01/02, Runway Overrun during Landing, American Airlines Flight 1420, MD-82, N215AA, Little Rock, Arkansas, June 1, 1999

3.1. Checklist Events

Checklist related events often play a role in aircraft incidents and accidents. They have been the frequent subjects of study (e.g., Degani & Wiener, 1990; 1993; Turner & Huntley, 1991, NTSB, 1994b). Employing voice technology to support the automation in executing checklists with the single pilot is a significant change and yet, current two-person procedures provide a model first to be emulated and potentially made more robust. One challenge is to take advantage of the capability of the automation to assure that a checklist item is never skipped, while retaining the flexibility to address anomalies in checklist processing.

Within the small sample of accidents reviewed, we briefly outline the checklist related events from two of the accident reports. Interruptions to checklist processing can lead to checklist items being skipped. This and the failure to execute a checklist can cause readily detectable problems to remain undiscovered. Beyond simply being required, executing checklists is recognized by everyone as being essential to safe aircraft operation, and yet, checklist processing omissions and errors continue to be a factor in aircraft incidents and accidents. We include checklist events in our brief overview, because, as the two examples below illustrate, the often-repeated reminder to diligently prosecute checklist bears repeating once more.

AA1420 was approaching Little Rock, Arkansas runway 4R under very difficult weather conditions including windshear alerts. In executing the Before Landing checklist, the items after checking the landing gear were not addressed (NTSB, 2001). The items related to the spoiler lever and the autobrakes were not executed and the spoilers were not armed. Following touchdown, neither the captain nor the first officer deployed the spoilers when they failed to deploy automatically. The failure to deploy the spoilers “lead directly to the flight crew’s problems in stopping the airplane within the remaining available runway length and maintaining directional control of the airplane on the runway.” (NTSB, 2001).

As COA1943 approached runway 27 at Houston Intercontinental Airport, the aircrew made two checklist related errors. “Fifteen minutes before landing, as the airplane descended through 19,000 feet, the captain omitted one item on the In-range checklist. The omitted item, ‘Hydraulics – ON & HI, CHECKED,’ would have enabled the high pressure configuration of the hydraulics system, thereby providing pressure to operate the flaps and landing gear.” (NTSB, 1997). The first officer later called for the Landing checklist and nine seconds later called for flaps 40 and then flaps 50. The captain did not initiate the Landing checklist in which checking the landing gear status was the first item. The first officer after suggesting a go-around, offered the captain control of the aircraft and the captain continued the landing with the failure of the landing gear to deploy undetected.

3.2. Problem Solving Tunnels

Approach and landing is a busy time for an aircrew—having a recognized problem that must be attended to, adds an additional stress factor. The problem is further compounded when terrain factors make the approach more difficult or when there is a severe weather situation. For some problems, a solution is readily adopted and the impact of the problem on the approach is minimal. In other cases, the solution may be elusive. When this happens, slow, thoughtful problem-solving is necessary and time management becomes a factor. Spare time available to address a problem is scarce and must be carefully managed. The slow thoughtful work of problem solving contrasts sharply with the fast-paced execution of the well-practiced landing procedures. A balance must be struck between the time devoted to the problem and that devoted to completing the approach and landing procedures. There is a risk that the problem can consume an inordinate amount of time and attention—essentially drawing the aircrew into what can be described as a "problem solving tunnel"—attention that is more urgently needed for immediate approach and landing tasks is devoted to the slow process of problem solving. The problem will be exacerbated in single pilot operation. The option of having the first office flying the aircraft while the captain focuses on the problem at hand will not be available. This is an issue that will need to be explored through simulation use cases as suggested in Section 4. A problem-solving tunnel played a significant role in the 1972 Eastern Airlines L1011 accident in the Florida Everglades (NTSB, 1973). It was also a factor in two of the accidents reviewed for this research effort that we briefly outline here.

The captain of AIA808 elected to land on runway 10 at Guantanamo Bay, Cuba where "The proximity of the runway 10 threshold to the boundary fence between U. S. and Cuban territory, places a burden upon pilots landing on runway 10." (NTSB, 1994a) The tower controller noted the strobe light on a U. S. Marine guard tower marking the boundary of the designated airspace for the approach. The aircrew was *not* notified that the strobe light was not working at that time. For the next minute and 57 seconds, the captain made several comments on his unsuccessful attempts to locate the strobe. Attempts by the first officer and flight engineer to alert the captain to the decreasing airspeed were not acknowledged, as he remained focused on his attempts to locate the strobe light. The aircraft subsequently "collided with level terrain approximately _ mile from the approach end of runway 10." (NTSB, 1994a)

During the CAL1943 approach to runway 27 Houston Intercontinental Airport (NTSB, 1996), the aircrew failed to set the DC-9's hydraulic power to "HI" leaving the flaps and landing gear inoperative. They had inadvertently skipped the checklist item for the hydraulic power setting. The first officer as pilot-flying called for slats and flaps 5 at 0859:00, and flaps 15 at 0900:13. The CVR suggests that at 0900:33 the captain first noticed a problem with the flaps: "I think the flaps (unintelligible word)." The first officer called for "gear down" at 0900:38 and the "landing check(list)" at 0900:41. The captain did not execute the landing checklist. The first item on the unexecuted checklist was the pilot-not-flying challenge of "gear," with the nominal response of "down, 3 green." The landing gear problem went undetected. During this time period, the cockpit voice recorder included repeated "sounds similar to the landing gear warning horn" and a "sound of tone similar to altitude alert." The aircrew still did not appear to recognize the landing gear problem. The first officer suggested a go-around and then offered control of the aircraft to the captain who proceeded with the landing. While not explicit, the evidence suggests that the captain was caught in a problem-solving tunnel. The "problem" capturing the captain's attention was the failure of the flaps to deploy. His response to the landing gear warning horn was to cycle the flaps lever so that it was set to less than fifteen degrees. This action did, in fact, silence the landing gear warning horn for a period of eight seconds, but it appears to have been an action aimed at addressing the flaps problem and not one focused on the unrecognized landing gear problem. That the captain continued with the landing suggests that the landing gear problem had still not been recognized. The high approach speed (due to the flaps not actually being deployed) deprived the aircrew of problem-solving time and lent further focus to the flaps problem. The principal situational events to which the captain responded were related to the flaps problem and the pursuit of the landing—CAL1943 landed on runway 27 with its gear up.

3.3. Biasing of a Decision

Factors contributing to a decision can come from many sources. They carry a bias on one side or the other for the outcome of the decision in which they play a role. They can sometimes play a role in a decision to which they might better not be linked. This is a problem area that will simply carry over to single pilot operations.

The aircrew for the AA965 flight into Cali, Columbia had an extended discussion on the time at which the cabin crew would be able to report for the next morning's flight (Aeronautica, 1995). The exact timing was not resolved, but there was clearly a cabin crew rest-scheduling problem. A short while later the captain suggested that the first officer "keep the speed up in the descent, I'd, it would help us… ." The comment suggests that he was sensitive to the crew-scheduling problem. When the Cali approach controller offered a straight-in approach to runway 19, the captain accepted the offer. The first officer noted that "we'll have to scramble to get down," and the captain requested "a lower altitude right away" from the controller. The aircrew recognized that they were creating a time-pressured situation, but could not foresee the consequences. It is of course, impossible to know if the decision with respect to the straight in approach would have been different had the aircrew not had the discussion about the cabin crew's rest scheduling problem. In the move to single pilot operation, the problem will be will us largely as with the two-person aircrew.

3.4. Missing Knowledge

Small items of missing knowledge can have a disproportionate impact. The aircrew of CO1943 on its approach to Houston Intercontinental Airport runway 27 inadvertently skipped the in-range checklist item to verify that the hydraulic pressure on their DC-9 was set to high. As they were trying to understand the problem that they were having with the failure of the flaps to deploy they also failed to realize that the landing gear had failed to deploy and lock. It appears that neither crewmember recognized the problem as the setting of the hydraulic pressure—it had to be set to high for the flaps and landing gear to operate (NTSB, 1997) and they had failed to make this change in the setting in preparation for the landing.

The aircrew of AA965 into Cali, Columbia had difficulty with information related to the ROZO-1 arrival with TULUA as the entry point to the arrival and with the ROZO radio beacon. They failed to recognize TULUA (ULQ) as the entry point to the ROZO-1 approach and elected to go direct to ROZO. They subsequently failed to recognize that the "R" entry for FMS route planning was interpreted by the FMS as ROMEO rather than ROZO (Aeronautica, 1995) taking the aircraft off their intended approach path.

In each of these cases, small items of knowledge recalled at the appropriate time might well have led to a different situation outcome. In single pilot operations, there will be only one crewmember as the source for needed knowledge.

3.5. Errors of Omissions

Errors of omission are often hard to detect and sometimes undetectable. AA1572 was approaching runway 15 at Bradley International Airport at night in a rapidly deteriorating weather situation. On initial radio contact with the approach controller, the controller failed to provide the latest information for their altimeter setting. The crew did not request a value for the setting; apparently; they did not notice the omission (NTSB, 1996). At the tower controller shift change, the controller being relieved failed to tell the relieving controller that the ATIS needed to be updated (NTSB, 1996). In a situation with falling barometric pressure, several opportunities were missed through which the aircrew might have been reminded to update their altimeter settings with the latest available value.

On their approach to the U. S. Naval Air Station Runway 10 at Guantanamo Bay, the tower controller notified the aircrew that "Cuban airspace begins three quarters of a mile west of the runway. You are required to remain within this, within the airspace designated by the strobe light." (NTSB, 1994a). The controller did not notify the aircrew that the strobe light was inoperative. While attempting to execute a challenging landing, the captain devoted a great deal of attention to the unsuccessful attempt to locate the strobe light.

In single pilot operations, there will be one fewer crewmember for the difficult task of catching errors of omission, compounded by the fact that it is one's own errors that must be caught.

3.6. Communicating in Challenging Situations

In fast-paced, challenging situations, person-to-person communication can break down in different ways. As the captain of AIA808 was attempting the challenging approach to runway 10 at Guantanamo Bay Naval Air Station, both the first officer and the flight engineer recognized the deteriorating situation with respect to airspeed and made repeated attempts to get the captain to address the problem. In their roles as subordinate crewmembers, they repeatedly provided *status* information on the deteriorating situation, rather than *command* increased thrust as the solution to the problem. When the captain finally responded by increasing engine thrust, it was too late to avoid the accident (NTSB, 1994a).

On their approach to Charlotte runway 18R, the US1016 captain acted on the increased airspeed by ordering the first officer to execute the go-around as they had pre-planned it (NTSB, 1995). He subsequently ordered the first officer to go to maximum power and then to "down, push it down." Each of the command communications was acted on quickly by the first officer. Shortly after the last command, the aircraft transitioned from fifteen degrees nose up to five degrees nose down severely compromising their chances of escaping the microburst. Unlike the AIA808 situation, the communications operated effectively, but the last command was flawed and the flaw was not recognized.

As AAL1572 approached runway 15 at Bradley International Airport, the first officer was monitoring the minimum descent altitude (MDA). The aircrew had not established a visual descent point (VDP); hence, the first officer was also looking out the windshield for the airport. Upon looking back at the instrument panel, he noted that the aircraft had descended below the MDA and notified the captain as pilot-flying: "Your going below your …" (NTSB, 1995). The captain did not take manual control of the aircraft to recover to the MDA (NTSB, 1995).

The events described raise the issue of error monitoring in the automation to support single pilot operation, much like that provided by the second crewmember in the two-person cockpit. The role for error monitoring, well beyond the reach of the current study, will need to be addressed in designing the automation to support single pilot operation.

3.7. Unacknowledged Situational Alerts

Situational alerts are normally expected to be effective and helpful in addressing a specific problem. The sounding of the landing gear warning horn should draw attention to the status of the landing gear. Unfortunately, there are cases in which the intended recipients do not seem to correctly process or act on the alert. The alert may be an auditory flight deck system alert, as discussed above, or a verbal communication from another aircrew member. There may be ongoing tasks that appear to monopolize attention, or the alert may be interpreted incorrectly.

Voice technology can be used to replace the landing gear warning horn, but there is no assurance that the spoken alert will be better attended—spoken alerts can go unprocessed as seen in the situations cited below. Situational alerts and their processing is an area needing further attention independent of the move to single pilot operation. Two of these events from the NTSB reports that were reviewed are outlined here. An appropriate response to each of these events might have led to better situation outcomes.

On the approach to runway 27 at Houston Intercontinental Airport, the aircrew of COA1943 had failed to set the DC-9's hydraulic pressure to high; hence, both the flaps and the landing gear were inoperative. In attempting to sequence the flap settings for the landing, the crew recognized that the flaps were not deploying and were working on the problem. When, as reported in the cockpit voice recording transcript (NTSB, 1996), a sound like the landing gear warning horn sounded, each crew member commented on the landing gear status, but apparently neither crew member determined that the landing gear was not actually down and locked. They subsequently landed the aircraft with the landing gear up. A specific and timely alert failed to elicit an appropriate response.

The captain of AIA808 had elected to fly the more difficult approach to runway 10 at the U. S. Naval Air Station at Guantanamo Bay, Cuba rather than the straightforward approach to runway 28. In this case, the alerts calling attention to the "deteriorating flight path and airspeed conditions" (NTSB, 1994a) were from both the first officer and flight engineer. Subsequently, the stall warning stick shaker activated, but there was no evidence that the captain attempted to take proper corrective at the onset of the stick shaker alert (NTSB, 1994a). The captain was focused on locating a strobe light that indicated the boundary between the air station and Cuban territory. The air traffic controller had notified the aircrew of the strobe, but failed to disclose that it was not operational. When the captain finally acted to correct the deteriorating situation, it was too late to avoid the accident.

3.8. Time-risk Relationship

The relationship between time and risk becomes more critical as aircrew task load increases. During approach and landing, aircrew task load is high making it important to understand and track this relationship. An action or event that reduces time available to the aircrew carries with it an increase in risk. The effect is the same whether there is now less time in which to complete a given set of tasks or whether the event or action has resulted an increased task load to be accomplished in the same amount of time. By being aware of the time-risk relationship and factoring it into its decision-making processes an aircrew can maintain a better assessment of their current risk and thereby better manage risk.

As can be seen in the following instances, the time-risk factor can go unattended in addressing fast-moving, complex situations. Single pilot operation can only exacerbate this problem—here again, in formulating procedures for single pilot operations, attention is needed to improve the ability of the single pilot to recognize and address the problem of increasing risk as the time to complete necessary tasks shrinks.

Management of the time-risk relationship was a factor in several of the accidents reviewed in this study. Our purpose here is not to judge the particular decisions, but rather to draw attention to the dynamics of the particular situations and examine how the time-risk factor played out. In two instances, explicit decisions were made that reduced the time available to complete approach and landing procedures. During the very early stages of the approach to the Cali airport, the AA965 aircrew had conducted an extended discussion of the cabin crew's crew-rest situation with respect to the following morning's flight. Rightly or wrongly, the discussion can reasonably be assumed to have created a bias to select an option that would lead to an earlier arrival time. Following that discussion, air traffic control offered such an option—a straight-in approach to runway 19. In accepting the offered straight-in approach, the response was: “uh yeah, we’ll have to scramble to get down. we can do it.” (Aeronautica, 1995) In this case, the crew clearly recognized that the decision reduced the time available to complete the approach and landing. The following dialogue makes no explicit reference to risk.

On AA1420’s approach to Little Rock runway 4R in a difficult weather situation, air traffic control was guiding the aircraft in for the landing following an initial approach to 22L. The air traffic controller noted that the aircraft would join the final approach just outside the outer marker and asked if that was okay. The aircrew accepted the close-in turn onto the final approach. In this instance, the aircrew did not note the associated time compression nor was there any explicit mention of risk. This was a very difficult landing in which the time-risk factor was just one of several in play at this point in the approach. While the situation implied that there would be less time to establish a stabilized approach, it did not appear to play a role in the decision to accept the short final approach.

The first two instances each involved an explicit decision that, in effect, reduced the time available to complete necessary procedures. In another time-compression instance, the factor that reduced the time available was not related to an explicit decision and went unrecognized. On the CO1943 approach to Houston Intercontinental Airport runway 27, the aircrew was addressing the problem of the failure of the flaps to deploy. During the completion of the descent checklist, the aircrew had established a target approach speed of 132 knots (NTSB, 1997). “The airplane was traveling at 216 knots indicated airspeed, approximately 504 feet above field elevation (AFE), and 34 seconds from touchdown.” (NTSB, 1997). “… the airplane was traveling at 204 knots indicated airspeed, approximately 161 feet AFE, and 12 seconds to touchdown.” With an airspeed 84 knots higher than the targeted airspeed, the aircraft’s progress along the final approach path was more rapid than the planned nominal approach depriving the aircrew of the time needed to address the recognized flaps problem. With more time available, they might have executed the required landing checklist and immediately detected the unrecognized failure of the landing gear to deploy. Or recognizing the time-compression, they might have elected to go around to provide time to address the unresolved problem.

4. Next Steps

Establishing policies and procedures for single pilot operation of commercial aircraft will be a formal FAA-guided process. In this section, we suggest some immediate next steps that might be pursued well before the formal process gets underway. Our intent is twofold: first, to vet the initial ideas that have been presented in this study based on voice technologies and agent-based systems. Second, we suggest stepping back to take a more deliberate top down approach that seeks to establish a philosophy, develop policies (Degani & Wiener, 1994), and proposes and evaluates procedures for single pilot commercial aircraft operations. Within this framework, a broader mix of technologies and procedures should be examined and evaluated. A review of the U. S. Air Force Pilot’s Associate program (Lockheed, 1990; 1993; Banks & Lizza, 1993) and U. S. Army Rotocraft Pilot’s Associate program (Miller & Hannen, 1999) that includes, in particular, an assessment of the requirement for error monitoring should be included in the broader review.

The following considerations apply both to the approach pursed in this study and to the early stages of the suggested broader process. In either case, the involvement of the pilot community should begin as soon as possible. The existing cognitive task analysis (Keller & Leiden, 2002) has provided us with good insight into normative approach, landing, and taxi operations. A cognitive work analysis (Rasmussen et al., 1994; Vicente, 1999; Naikar et al., in press) would provide insight into the work of the flight deck that focuses more closely on how it is actually performed. To fully understand the challenges presented by single pilot operations, it will be important to identify the essential contributions of the pilot-not-flying that we do not see in the formal description of the pilot-not-flying tasks and responsibilities.

With respect to our approach, we are suggesting that the pilot-not-flying tasks be taken over by automation that emulates current pilot-not-flying task execution. It will be important to identify those elements of the pilot-not-flying tasks that the automation is not able to adequately address. These will be the points at which the single pilot may be faced with additional workload. The analysis should extend across the phases of flight beginning with pre-flight activities and carry through taxi operations and shutdown. A series of use cases should cover nominal operations, as well as challenges to the aircrew presented by weather or aircraft equipment issues.

A separate line of inquire should directly solicit ideas and recommendations on single pilot operations from the pilot community. As initial ideas are refined to become proposed operating procedures, the dialogue should be extended to include the airlines and aircraft manufacturers in whose hands the final operational procedures will be developed and deployed.

Simulation provides multiple levels at which new approaches to the automation and aircrew procedures may be evaluated. Existing human performance models for aircrews and controllers, and airspace sector models may readily be adapted to provide a first line of inquiry for single pilot procedure evaluation. The simulation of the single pilot, the automation, and their interactions would include a prototype agent-based implementation of the automation and yield a first evaluation of the proposed role established for the automation. The fast-time modeling environment using a human performance model for the single pilot and automation modeled closely on pilot-not-flying functionality can be predicted to yield encouraging results. The more challenging problem is to extend the initial trial scenarios and then probe those scenarios to begin to better understand potential shortfalls and sources for error in the interactions between the single pilot and the proposed automation.

There are then a series of questions to be addressed using human-in-the-loop simulation. As the dialogues to be supported by voice technology are developed, it will be important to use part-task simulation to start the process of understanding the limits of the capabilities that can be supported using voice technology and begin to gain an understanding of the fine structure of the dialogues necessary to sustain safe and efficient flight deck operations. Pilot acceptance of the use of voice technology will need to be established if the proposed approach is to be successful. At the same time it will be necessary to determine the level of performance that can be achieved by voice technology under the noisy conditions of the actual flight deck environment and gain an understanding of how that performance should be interpreted in terms of requirements for safe and efficient use on the flight deck.

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Appendix A. Aircrew Models for Approach, Landing, and Taxi Operations

We have been modeling aircrew and air traffic controller performance for a number of years using D-OMAR as the modeling and simulation environment. This section is included to provide background information on the aircrew models focusing on approach, landing, and taxi operations. The models and scenarios described here will form the basis for the modeling and initial evaluation of single pilot procedures and the supporting automation.

The models for the captain and first officer work together to safely execute the approach, landing, and taxi procedures. In responding to a series of controller communications, actions are prioritized, appropriate intra-aircrew communications are generated to coordinate the execution of these actions, and interrupts in the form of further communications from the controllers are handled. The interrupts are not unexpected, but rather meet expectations consistent with established procedures, local air traffic, and weather conditions. Reactive behaviors are determined within the framework of the aircrew's active goals and procedures. In meeting their responsibilities, the captain and first officer have a significant number of tasks in process, each of which requires a coordinated mix of perceptual, cognitive, and motor skills. The scenarios create situations in which the response to demands must be prioritized to achieve acceptable performance.

Each aircraft is populated by human performance models for the captain and first officer. The current aircrew models are extensions of recent modeling efforts that examined taxi errors following an ILS approach and landing at O'Hare airport (Deutsch & Pew, 2001; 2002a) and SVS-equipped landings at Santa Barbara Municipal airport (Deutsch & Pew, 2002b). The procedures that our models execute are adapted from the Keller and Leiden (2002) task analysis. The description that follows traces the nominal approach with the captain as the pilot-flying and first-officer as pilot-not-flying. The Charlotte scenarios (Deutsch & Pew, 2004a; Deutsch, 2005), on the other hand, were flown with the first-officer as pilot-flying and the captain as pilot-not-flying.

The modeled approach and landing scenario closely follows the standard progression in the airspace transiting from approach controller to tower controller to ground controller, terminating as the aircraft completes the landing and taxies to its assigned concourse. In the modeled scenarios, like the aircrew, each controller is represented by a human performance model. Communication among aircrews and controllers is via party-line radio. In a more recent ongoing study, the primary mode of communication is data link augmented by radio communication when necessary.

The aircraft model includes flight deck instruments and controls necessary for the crew to execute the required approach and landing scenario. The principal instruments include the PFD, and the HSI. Controls include the MCP, switches for the autopilot, and levers for the throttles, flaps, landing gear, and speed brakes. The central instrument panel includes lights for landing gear status. Equipment such as data link or the SVS is included when required by the specific scenario.

The aircrew makes use of the approach plate for the assigned runway for information related to the approach. In a nominal scenario, the information derived from the approach plate is used by the captain to brief the go-around contingency at the beginning of the approach. The approach plate is subsequently used by the aircrew as a reference to track the sequence of fixes for the approach path and as the source for the required descent altitude for each approach leg. Following the landing, as the aircraft departs the active runway, the first officer uses the airport diagram to support taxi operations leading to the concourse.

Voice communication between the captain and first officer is used to coordinate the execution of approach and landing procedures. Party-line radio communication is modeled with the aircrew resetting radio frequencies as they move from one controller to the next. Careful attention has been paid to the fine details of interleaving of aircrew and air traffic controller conversations and to handling air traffic controller interruptions to aircrew conversations. When data link is used, the pilot-not-flying will read the data link messages to the pilot-flying.

As the nominal scenario begins, the approach controller first clears the aircraft for the approach to the designated runway. The captain elects to fly the approach as either pilot-flying or pilot-not-flying. Using information from the approach controller and the approach plate for the runway, the pilot-flying continues the approach by reviewing the runway and weather information with the pilot-not-flying.

The aircrew then focuses on navigation as the aircraft proceeds along the flight management computer (FMC) flight path from one fix to the next. The aircrew monitors the aircraft's heading and altitude changes (base on information information derived principally from the HSI) as the aircraft transitions onto the leg to the next fix. They continue to monitor the heading until the new desired heading is fully established. They monitor altitude to assure that they hold at the selected target altitude. As the approach progresses, the pilot-flying calls for a series of flap settings consistent with their speed and position along the approach path.

The approach controller subsequently directs the aircrew to contact the tower controller. The pilot-not-flying contacts the tower, they receive the clearance to land and are provided with information on wind speed and direction.

Next, the aircrew configures the aircraft for landing. The pilot-flying calls for "gear-down," the pilot-not-flying engages the landing gear and makes the call-out. The pilot-flying adjusts the speed for landing, makes the call-out, and then calls for the final flaps setting. The pilot-not-flying sets the flaps and makes the call out. The pilot-flying then calls for the final descent checklist. The pilot-not-flying verifies that the spoilers are armed, the landing gear is down and locked, and the flaps are set for landing, makes the call-outs and confirms the completion of the checklist.

At this point, the aircrew is monitoring the final descent profile. The pilot-not-flying monitors the aircraft's altitude and makes call-outs at 1000 feet, 500 feet, and "minimums." The pilot-flying announces "landing," the pilot-not-flying calls out 100 feet, and the aircraft touches down. The pilot-flying and pilot-not-flying "sense" weight-on-wheels, the pilot-flying applies reverse thrust and disarms the autobrakes. The pilot-not-flying verifies that the thrust levers are closed and the speedbrakes are up. The pilot-not-flying then monitors the aircraft's ground speed and makes call-outs at 100, 90, 80, 70, and 60 knots. At this point, the landing is complete and transition to taxi operations is about to take place. The aircraft model provides each of the controls required by approach-and-landing sequence as outlined here. The aircrew executed each of the required steps and monitored the approach as indicated.

As the aircraft slows to taxi speed, the aircrew prepares to take the designated exit from the runway with the captain in control of taxi operations. The first officer reviews his/her notes and the airport diagram and notifies the captain of the aircraft's location with respect to the designated exit. The captain disengages the autopilot and monitors the runway signage for the runway exit. At the aircraft approaches the exit, the first officer notifies the tower controller that the aircraft is clearing the runway, the aircrew switches their radio frequencies to that of the ground controller and the first officer notifies the ground controller that the aircraft has cleared the runway. The ground controller responds with the taxi clearance. The captain monitors the communication while first officer takes notes on the taxi sequence.

The aircrew then follows a basic procedural pattern in executing the taxi operations. As each turn is completed, the first officer reviews his/her notes for next turn in the taxi sequence, checks the airport diagram for turn location and taxiway geometry, and notifies the captain of the upcoming turn providing additional details as the required by the geometry of the taxiway layout. As the captain controls the progress of the aircraft, the captain and first officer (when not head-down) scan the out-the-window view for traffic. The captain monitors and calls out the airport signage, tracks the current centerline for the next turn, and announces each turn as he/she executes it. The pattern is then repeated until the final taxiway and the approach to the concourse gate.