Conceptual Framework for Single Pilot Operations

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ABSTRACT
Single pilot operations (SPO) refers to flying a commercial aircraft with only one pilot in the cockpit, assisted by advanced onboard automation and/or ground operators providing piloting support services. Properly implemented, SPO could provide operating cost savings while maintaining a level of safety no less than conventional two-pilot commercial operations. A concept of operations (ConOps) for any paradigm describes the characteristics of its various components and their integration in a multi-dimensional design space. This paper presents key options for human/automation function allocation being considered by NASA in its ongoing development of a SPO ConOps.

Keywords
Single pilot operations, concept of operations, function allocation, crew resource management.

1. INTRODUCTION
Many aircraft, such as small private airplanes or military fighters, are operated with a single pilot in the cockpit. However, U.S. federal aviation regulations (FARs) currently require a cockpit crew of at least two pilots for most commercial air carriers. The cost associated with crews (salaries, benefits, training, etc.) is a significant fraction of the aircraft operating cost, especially for regional/commuter operators that typically fly smaller aircraft with fewer seats than major airline operators that fly narrow/wide-body aircraft (see Fig. 1). Additionally, current trends indicate a possible shortage of qualified pilots in the future [1]. Crew cost and availability issues provide the motivation to explore the feasibility of safely operating a commercial aircraft with a single pilot in the cockpit assisted by advanced onboard automation and ground operators providing flight support services well beyond those currently delivered by aircraft dispatchers.

This new paradigm is termed Single Pilot Operations (SPO). A key requirement of SPO is to maintain safety at a level no less than current two-pilot operations by the introduction of advanced cockpit automation and new ground operator positions using support tools and air-ground communication links. SPO will yield economic benefits if the costs of new ground operators and advanced automation are surpassed by the savings from a ~50% reduction in cockpit crew costs. In addition to the primary cost savings arising from eliminating the first officer position, there will likely be secondary savings due to better crew connection integrity and smaller/lighter cockpits in next-generation commercial aircraft designed for single-pilot operations.

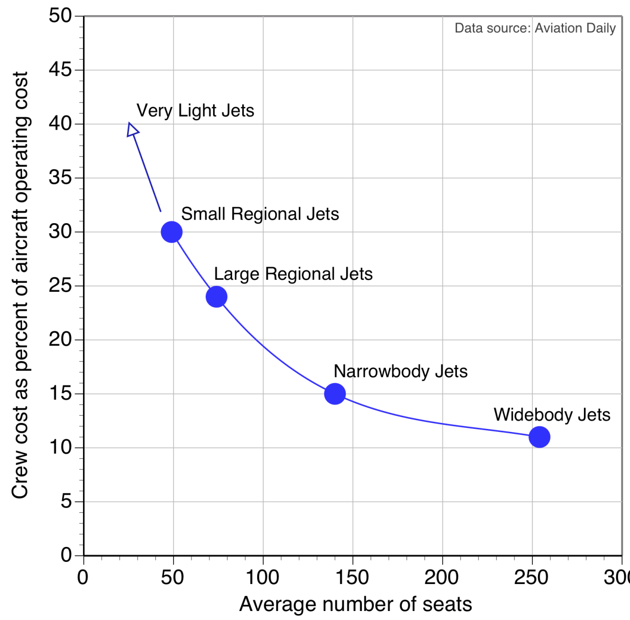

Figure 1. Crew cost vs. number of seats

NASA is conducting research on SPO feasibility under its Airspace Systems Program [2]. Some aspects of SPO are also being researched in Europe under the Advanced Cockpit for Reduction Of Stress and Workload (ACROSS) program [3]. An important element of NASA's SPO research is the development of a concept of operations (ConOps) that covers the roles and responsibilities of the principal human operators, the automation tools used by the humans, and the operating procedures for human-human and human-automation interactions. This ConOps is being constructed using insights gained from a variety of sources

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including subject matter experts, human-in-the-loop experiments examining key aspects of the ConOps, and cost-benefit analyses.

This paper presents key options for human/automation function allocation being considered by NASA in its ongoing development of a SPO ConOps. It is beyond the scope of this paper to explore all options in the ConOps design space. The options presented here were selected by the research team based on insights drawn from subject matter experts participating in an SPO technical exchange meeting [4] and knowledge gained from initial human-in-the loop experiments studying specific aspects of SPO [5, 6]. Section 2 provides a brief history of the evolution from a five-person cockpit to the current two-person cockpit, and outlines some implications of one-person cockpit operations. Section 3 presents a taxonomy of operating conditions for SPO, to establish high level requirements for operator functions and equipment. Section 4 presents key options for function allocation among various types of human operators, while Section 5 describes considerations for human-automation function allocation. Some concluding remarks are presented in Section 6.

2. COCKPIT CREW COMPLEMENT

SPO may be regarded as the next phase of a decades-long downward trend in the number of cockpit crew required for safe operations. In the 1950s, commercial aircraft typically had five cockpit crewmembers: captain, first officer (co-pilot), flight engineer, navigator, and radio operator. Advances in voice communication equipment removed the need for a dedicated radio operator position. Next, advances in navigation equipment (e.g., inertial navigation systems) removed the need for a dedicated navigator position. Finally, advances in monitoring equipment for engines and aircraft systems removed the need for a dedicated flight engineer position.

Over the past 25 years or so, commercial aircraft have operated with a two-person cockpit (captain and first officer). It is important to note that the functions associated with the radio operator, navigator, and flight engineer positions did not simply disappear – they are now performed by the captain and/or first officer, assisted by cockpit equipment that has greatly reduced the human workload originally required to perform those functions. This new equipment along with new flight deck procedures have preserved or increased flight safety, even with a reduced crew. Economic benefits have been realized because the savings from reduced cockpit crew expenses have exceeded the costs of equipage.

The transition from a two-pilot cockpit to a single-pilot cockpit will be significantly more challenging than the transitions from a five-person cockpit to a two-person cockpit. Unlike the previous transitions, it may not be possible to assure safety of SPO simply by adding new automation to the cockpit. There will likely be situations where the single pilot in the cockpit needs to collaborate with a person on the ground to solve a complex problem. There is also the issue of single-pilot incapacitation, which could be addressed by a ground operator directing advanced cockpit automation.

Implementation of SPO involves a transition from the current paradigm of a Captain, First Officer, and Dispatcher team using conventional automation tools, to a new paradigm of a Captain and Ground Operator team interacting with advanced human-centered automation tools (see Fig. 2). Although many of the functions currently performed by the first officer could be performed by some combination of ground operators and advanced automation under SPO, there is an opportunity for a "clean-slate" allocation of functions for Captain, Ground Operator, and Automation. This clean-slate approach to SPO would result in a new/different model for crew resource management (CRM).

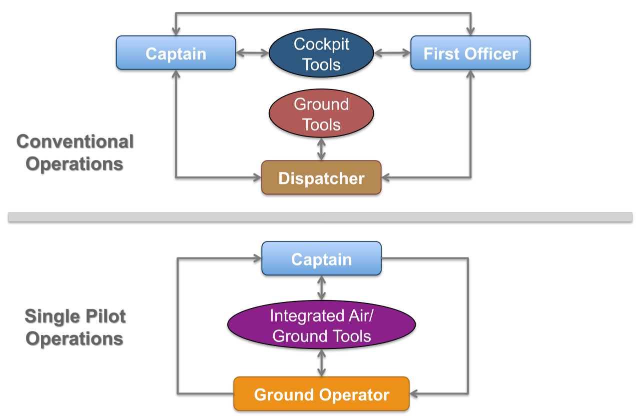

Figure 2. Conventional vs. single-pilot operations

3. TAXONOMY OF OPERATING CONDITIONS FOR SPO

The characteristics (e.g., roles/responsibilities, tools, procedures) of an SPO ConOps will depend in part on the nature of the operating condition. A basic taxonomy is presented in Fig. 3, based on the pilot's physiological and behavioral condition (normal vs. incapacitated) and flight condition (nominal vs. off-nominal). It is noted that the term "flight condition" refers to the myriad factors affecting the flight other than the pilot's condition, such as the status of aircraft systems, weather conditions, and airport availability.

As the taxonomy condition (TC) progresses from 1 to 4, the operating conditions become more challenging, and the requirements for safe implementation of SPO become more complex. For example, in TC–1, there may not be much need for ground operator assistance; the cockpit automation could provide most of the assistance needed by the captain. In TC–2, the captain would likely request the assistance of a ground operator, especially in complex off-nominal conditions with high cognitive workload. TC–3 would require a ground operator to assume the role of captain and interact with cockpit automation to land the aircraft. In

TC–4 the ground operator acting as captain may need assistance from other ground operators to land the aircraft.

		Flight Condition	
		Nominal	Off-Nominal
Pilot Condition	Normal	1	2
	Incapacitated	3	4

Figure 3. A taxonomy of operating conditions for SPO

Under SPO, it is assumed that an incapacitated pilot condition would be handled as a declared emergency, with air traffic control (ATC) providing special handling to the flight which would be directed to land by a ground operator interacting with advanced cockpit automation. A study [7] conducted by the FAA Aeromedical Institute for U.S. flights over the six-year period 1993–1998 found 39 instances of in-flight medical incapacitation, defined as a condition in which a flight crewmember was unable to perform any flight duties; the in-flight event rate was 0.045 per 100,000 flying hours. This corresponds, on average, to one incapacitation event per 1.85 months or per 2.2 million flying hours. Although these statistics may be somewhat different in the SPO implementation timeframe, the incapacitation rates would likely be low enough that declaring a pilot-incapacitation emergency would not unduly disrupt ATC operations.

The necessity for safely landing an SPO aircraft with an incapacitated pilot will be a key driver of technology requirements for cockpit automation, remote flight-control tools for the ground operator, and air/ground data links. The implementation of these technologies with sufficient reliability/redundancy will likely represent a significant part of the costs of implementing SPO. It is noted that some components of the technologies required for safe landing in an incapacitated-pilot scenario, such as autoland systems, are already available and in current use.

4. FUNCTION ALLOCATION FOR HUMAN OPERATORS

This section presents considerations for function allocation among the human operators on the aircraft and ground. Characteristics of functions performed by the captain and ground operators are described; this includes options for organization structures for ground operators. The material presented in this section is not intended to be an all-encompassing treatment of SPO options for function allocation among human operators; its scope is limited to the options being considered by NASA in its ongoing development of a ConOps for SPO. Function allocation between human operators and automation is discussed in Section 5.

4.1. Captain

The captain (unless incapacitated) serves as the pilot-in-command (PIC), making all decisions pertaining to command of the flight. As such, he/she bears the ultimate responsibility for safe and efficient operation of the flight. The captain is the final decision-maker regarding the flight mission, and (according to procedures) calls on automation and ground operator assets to accomplish this mission. The captain's main tasks are to manage risk and resources (both human and automation). Under SPO, the fundamental command/leadership role of the captain may not change, but the individual tasks and duties of the Captain will change significantly. The captain will likely take on some of the conventional Pilot Flying (PF) and Pilot Monitoring (PM) duties, while other PF and PM duties are allocated to the automation or the ground operators. The characteristics of the resources available to the captain will also be quite different, e.g., no first officer in cockpit, expanded menu of resources available from ground operators, new/advanced automation available in the cockpit. With this change in function allocation, a new CRM model will likely be required under SPO.

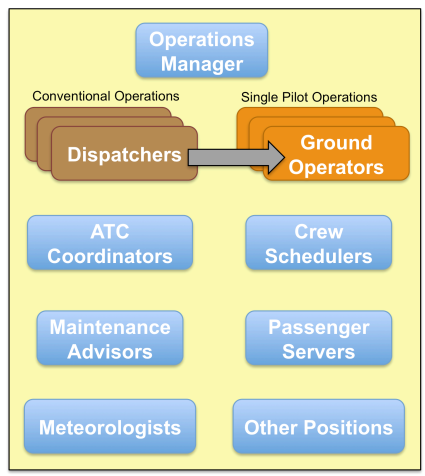

Figure 4. Representative layout of airline operations center

4.2. Ground Operators

In current operations, flights receive ground support services from their airline operations center (AOC). Figure 4 depicts key positions in a typical AOC, which is supervised by an operations manager. There are various AOC positions that provide specialized services, e.g., dispatchers, ATC coordinators, crew schedulers, maintenance advisors, customer servers, and meteorologists. It is anticipated that SPO would primarily modify the functions of the dispatchers, with limited impact on other AOC positions.

In current operations, each dispatcher serves around 20 aircraft that are in various phases of flight at different locations around the country or even the world. By U.S. regulation, the dispatcher shares responsibility with the captain for safe operation of the flight. A significant part of the dispatcher's duties lies in the pre-flight phase, where the dispatcher consults with the captain and uses various AOC tools to develop a flight plan (e.g., routing, cruise altitude, airspeed), determine fuel loading, meet weight and balance requirements, and ensure compliance with the minimum equipment list (MEL). After the dispatcher and captain sign the flight release, the dispatch functions transition to flight monitoring and serving as a conduit for information between the aircraft and the AOC. The dispatcher also plays an active role supporting the cockpit crew during off-nominal conditions such as aircraft equipment malfunctions, diversions to a different destination airport, and large (> 100 nmi) changes in routing. Dispatchers generally serve their flights all the way from pre-flight planning to gate arrival.

In SPO, dispatchers become ground operators (see Fig. 4) who collectively perform conventional dispatch functions as well as piloting support functions, although each ground operator does not necessarily perform both types of functions. Ground operator teams collectively perform the following three core functions: (1) *Conventional Dispatch* of multiple aircraft; (2) *Distributed Piloting* support of multiple nominal aircraft; (3) *Dedicated Piloting* support of a single off-nominal aircraft. The Conventional Dispatch function has been described above.

The Distributed Piloting function corresponds to basic/routine piloting support tasks such as reading a checklist, conducting cross-checks, diagnosing an aircraft system caution light, determining the fuel consequences of a holding instruction, etc. It is presumed that a single ground operator can provide such services to multiple aircraft because these non-urgent and relatively brief tasks can be prioritized and executed sequentially. This function would be applicable only to nominal aircraft, corresponding to Taxonomy Condition 1 defined in Fig. 3.

The Dedicated Piloting function corresponds to sustained one-on-one piloting support requested by the captain under high-workload or challenging off-nominal operating conditions such as an engine fire, cabin depressurization, or diversion to an alternate airport due to low fuel and/or bad weather, etc. This function is also applicable to situations where the ground operator has to take command of an aircraft whose captain has become incapacitated. The tasks associated with this function may include flying the aircraft, e.g., remote manipulation of the aircraft's flight management system (FMS) for route amendments, or remote manipulation of the aircraft's mode control panel (MCP) for sending speed/altitude/heading commands to the autopilot. The Dedicated Piloting function would be applicable to Taxonomy Conditions 2, 3, and 4 defined in Fig. 3. The skills and training required to perform the dedicated piloting support function are essentially the same as those of a conventional pilot. One possibility is a rotating schedule where a pilot is scheduled for several weeks of airborne (cockpit) assignments followed by a week of ground (AOC) assignments.

Ground operators will require tools similar to those on the flight deck for issuing high-level flight control commands such as making route changes in the aircraft FMS, or manipulating airspeed/altitude/heading commands via the MCP. The ground operator tool set may also include next-generation dispatcher tools to reduce workload. Additionally, SPO will require a secure and reliable air-ground link for voice and data communications. These requirements are similar to those currently being considered for unmanned aircraft systems (UAS) operations in the national airspace system.

There are many possible structures for organizing ground operators to perform the three core functions described above. While safe operation is the paramount concern, another key consideration is the operating cost associated with the ground operator team structure. One cost factor is the number of ground operators relative to the number of aircraft they can safely support, as well as the training/qualification requirements for those ground operators. Another cost factor is the number of ground stations that require complex and reliable (and hence expensive) equipment such as that required to remotely control an aircraft's flight-path. Cost/complexity of the ground operator support system can be traded off against cost/complexity of the cockpit automation support system (this will be discussed in Section 5). Two ground operator organization structures of interest, hybrid ground operator unit and specialist ground operator unit, are described below and illustrated in Fig. 5. These ground operator organization structures have been selected by NASA, based on subject matter expert opinion, for evaluation in an upcoming human-in-the-loop evaluation.

4.2.1. Hybrid Ground Operator Unit

In this organizational unit, each hybrid ground operator (HGO) is trained and certified to perform all three core functions: Conventional Dispatch tasks as well as Distributed Piloting and Dedicated Piloting support tasks.

Each HGO generally serves multiple flights from pre-flight planning to gate arrival. However, if/when one of these flights encounters an off-nominal condition that requires dedicated support, the other aircraft are handed off to several other HGOs under the direction of the unit's supervisor. Some of these handoffs may require a briefing if the involved aircraft need special handling instructions. The HGO then provides one-on-one support to the off-nominal aircraft, calling upon other AOC positions (e.g., maintenance advisors) as necessary. After the off-nominal situation is satisfactorily resolved, the aircraft previously handed off by this HGO are returned to him/her if they have not already landed.

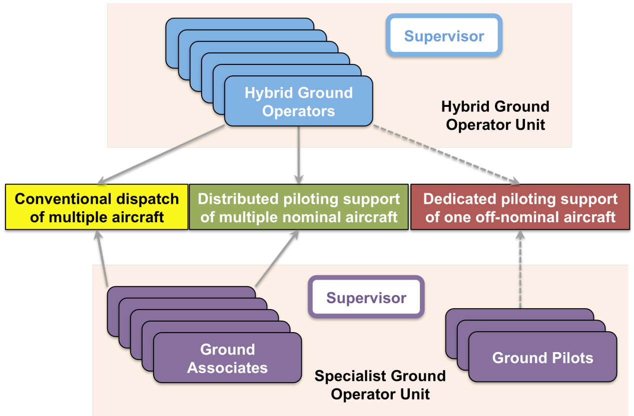

Figure 5. Examples of ground operator unit structures

4.2.2. Specialist Ground Operator Unit

In this organizational unit, there are two types of members. Ground Associates (GAs) are trained and certified to perform tasks associated with Conventional Dispatch and Distributed Piloting support for nominal aircraft. Ground Pilots (GPs) are trained and certified to perform tasks associated with Dedicated Piloting support for off-nominal aircraft. There would be many more GAs than GPs in these units.

Each GA generally serves multiple flights from pre-flight planning to gate arrival. However, if/when one of these flights encounters an off-nominal condition that requires dedicated support, that aircraft is handed off to a GP identified by a supervisor. Prior to the handoff, the GP may be on standby or performing collateral duties and would need a handoff briefing from the GA who was serving the off-nominal aircraft. The GP provides one-on-one support to the off-nominal aircraft. The GA maintains general situational awareness of the off-nominal flight in case the GP requires dispatch support or any other AOC support. After the off-nominal situation is satisfactorily resolved, the GP returns the aircraft (if it has not already landed) back to the GA.

4.2.3. Harbor Pilot

A harbor pilot is a type of ground operator serving as a member of a hybrid unit or a specialist unit (or any other type of ground operator unit). The function of a harbor pilot is similar to current practice in maritime operations. For example, there could be a harbor pilot with comprehensive knowledge of the metroplex airspace around the New York City area airports. Each harbor pilot provides distributed piloting support to multiple nominal aircraft as they climb and descend through a complex terminal area airspace. This could reduce the workload of other positions in the ground operator units, enabling each position to support more aircraft.

5. HUMAN-AUTOMATION FUNCTION ALLOCATION

This section presents some considerations for allocating functions between human operators and automation. First, the cost tradeoffs between automation and human operators are conceptualized. Next, some high-level requirements for new cockpit automation are introduced. Finally, some observations are made about desired collaboration between human operators and automation.

5.1. Options Space

In SPO, the captain (in the cockpit) and ground operators (in an operations support center), working as a team, will interact with advanced automation tools (located in the cockpit and at a ground station) to maintain flight safety and efficiency. Some of the simpler functions currently performed by a human pilot in a two-person cockpit, such as reading checklists and conducting cross-checks, are good candidates for automation, although such systems will have to possess some of the same characteristics as the operator they are replacing. Highly complex functions, such as formulating options to address challenging off-nominal flight conditions, are likely best suited to human cognition given the current state of automation sophistication and reliability. Other functions could be performed by humans assisted by various levels of automation; some preliminary recommendations are reported in [8]. Higher levels of automation will generally require fewer human ground operators to service a given fleet of aircraft. It is likely that there will be a progression, along the SPO implementation timeline, from a larger ground operator complement using lower levels of automation to a smaller ground operator complement using higher levels of automation.

Figure 6 is a notional representation of the relationship between the level of automation and the total number of operators required to support a fleet of aircraft at a given moment. In conventional operations, each aircraft has two pilots, and each dispatcher supports around 20 aircraft, hence a fleet of 100 aircraft needs a total of about 205 operators at a given moment. The cost of operations depends on the number and qualifications of the operators as well as the level of automation; therefore the cost of conventional operations is notionally proportional to the distance of the blue dot from the origin of the axes in Fig. 6.

The green oval represents the domain of various options for human-automation function allocations for SPO. Consider an implementation of SPO, indicated by "A" in Fig. 6, where each first officer is replaced by a ground operator. Hence the total number of operators remains the same, and a higher level of automation/equipage (e.g., air-ground voice/data links, ground pilot stations) is required. This instantiation of SPO has little merit because its implementation cost would likely not provide any savings relative to the baseline of conventional operations. Now consider an implementation of SPO, indicated by "B" in Fig. 6, where each first officer is effectively replaced by highly advanced cockpit automation (electronic pilot associate). The total number of operators is essentially cut in half, relative to the baseline of conventional operations. However, the cost to build such highly sophisticated automation would likely be very high and could result in either a cost advantage or disadvantage over conventional operations (or might simply be a wash as indicated in Fig. 6). A cost-effective solution is indicated by "C" in Fig. 6. Relative to conventional operations, it requires significantly fewer operators and significantly more automation, but much less automation than option "B". Noting that the distance from the axes origin is a proxy for cost, it can be seen that the overall operations cost for option "C" is lower than that of conventional operations (indicated by the arc in Fig. 6).

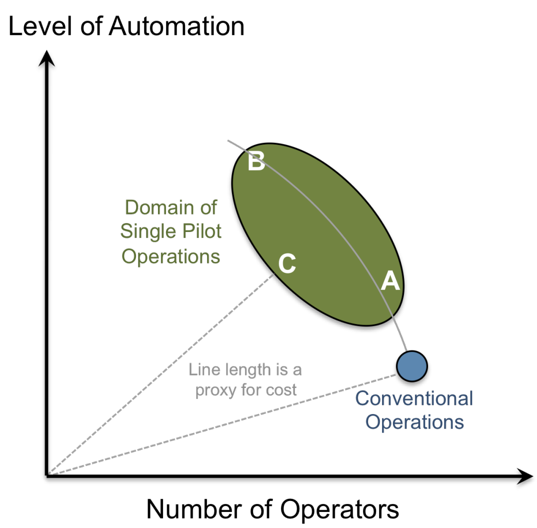

Figure 6. Options space for implementation of SPO

The development of an SPO ConOps requires an exploration of the options space outlined above, with the goal of identifying an SPO implementation that has characteristics similar to option "C" in Fig. 6. For a point of interest in the options space, a key question is: what are the requirements to implement this design of SPO at the same level of safety as conventional operations?

5.2. Cockpit Automation Requirements

A key requirement for SPO implementation is advanced automation [9] that provides onboard support functions at a level well beyond what is currently available in modern commercial aircraft. While it may be tempting to simply automate as many of the current pilot functions as possible, distancing the captain from the flight/mission could erode situation awareness (SA) and cognitive readiness. Over-automation would increase the likelihood of human error and thus handicap the captain. Therefore, there may be functions and tasks that could be automated from a technological standpoint, but should not be automated in order to maintain the captain's SA, engagement, and skill retention.

Some of the cockpit automation capabilities required for SPO already exist, e.g., nearly all modern aircraft can fly a preprogrammed route and land with little or no human aid. However, there are two important automation capabilities that require significant advancement: (i) interaction and task exchange, and, (ii) pilot health monitoring.

5.2.1. Interaction and Task Exchange

The capability development required here is to make the automation more of a team player, rather than a silent and subservient workhorse. This requires changes in the way the automation interacts with the human, rather than what tasks it performs. For example, cockpit automation needs to clearly inform the captain about what it is doing, and to confirm important parameters (e.g., altitude settings). In response to a command from the captain, the automation must repeat the command for error-checking, inform the captain that it is executing the command, and notify the captain when it is done. In short, the automation must follow current best practices for human-to-human CRM.

The automation will be called upon to assist the captain in declarative, retrospective, and prospective memory items. Required tasks of the automation may include checklists, task reminders, challenge-and-response protocols, and recall of information or instructions provided by human actors such as ATC personnel or ground operators. But these tasks cannot be rigidly prescribed. The human brings certain unique capabilities to the cockpit as does the automation. Both types of capabilities are required when performing basic interconnected tasks such as: Aviate, Navigate, and Communicate. It may be detrimental to assign one task (e.g., Aviate) entirely to the captain and leave the others entirely to automation. It is also highly unlikely that the level of automation assistance would remain constant for the entire mission; for example, the level of automation will change in the Aviate task, depending on whether the captain is manually flying or being assisted in some way by the automation.

The unique capabilities of the human and the automation may be required at different times. The captain and the automation have to be able to hand tasks back and forth between each other in a simple, quick, reliable, and well-understood fashion. This reallocation of tasks between them (or between the captain, automation and the ground operator) will likely be required in off-nominal or unique situations. In these times, workload on the human is already high, and if the captain has to "hand off" the aircraft to the automation in order to deal with a navigation or systems problem, he/she must be able to do so quickly and with full confidence. Similarly, if the automation has to hand control back to the captain because it is reaching its limitations, it must inform the pilot ahead of time and provide SA information to the pilot about why the hand off has become necessary (e.g., with what aspects the automation is having difficulty, or is unable to perform.)

5.2.2. Pilot Health Monitoring

The second automation capability that requires development is the monitoring of the captain's physiological and behavioral state. This health monitoring serves two purposes: assessing the capacity of the captain, and catching mistakes made by the captain. In multi-crew flight decks, the crewmembers monitor each other. It is unlikely that automation will advance to the full monitoring capability of a human crewmember in the timeframe of SPO implementation, but there are many important health factors that could be monitored by the automation.

Physiological sensors can assess health factors ranging from simple heart rate variability and pulse oxygen levels to more elaborate measures such as electro-encephalograms (EEG) and functional near-infrared spectroscopy (fNIRS). The challenge here is to make the measurements as non-intrusive and comfortable as possible – the idea of wiring the body with multiple sensors is highly undesirable for human acceptance. Still, technology continues to advance in remote sensing capability so that no physiological measurement should be ruled out at this point. These measurements would provide a primary basis for assessing whether the pilot is healthy and responsive.

Behavioral measures are also important. Monitoring the captain's actions with regard to instrument and inceptor control, communications, and scan patterns is critically important to detect piloting errors and to make assessments of cognitive capability. Prescriptive assessments, where the human's behavior is compared to what he/she should be doing at any particular time or after performing a particular task (e.g., Task A, then Task B, then Task C), are useful but are often overly rigid and not flexible for real-time operations. Another approach is to monitor the human's actions to ensure that he/she does no harm, that is, does not do something that would jeopardize the mission. More than likely, a combination of these two methods will be required.

Pilot health monitoring can also be performed by ground operators who can query the captain or watch a video feed of the cockpit to determine the physiological and behavioral state. This assessment, along with health monitoring data provided by the automation, will be the basis for a decision to declare the captain incapacitated and transfer command authority to ground operators and/or cockpit automation to land safely.

5.3. Collaboration

While it is important to describe the roles of each of the major players in SPO (Captain, Ground Operator(s), Automation), it is also important to remember that none of these players acts independently. In order for SPO to be feasible, each player must be able to shed and take on tasks and responsibilities as/when needed.

Not only is pilot incapacitation a critical concern, but the prospect of automation failure, and/or communications failure must also be addressed. If the automation is malfunctioning (e.g., stuck in a mode, erroneous flight data, software bug) or non-functional (e.g., total failure of autopilot, guidance, secondary systems), the captain and ground operators should be able to safely land the aircraft and perhaps safely complete the mission. Likewise, if the communications network is impaired (e.g., decreased bandwidth) or non-functional, the Captain and automation should be able to safely land or perhaps even complete the mission.

This flexibility is not only important in off-nominal conditions, but in nominal conditions as well. One example is when the captain has to leave the cockpit for a short break. In such cases, the automation will be flying the aircraft; however, the ground operator would be called upon to closely monitor the flight (and perform remote piloting functions as necessary) and update the captain on the flight's status when he/she returns to the cockpit. Similarly, the captain may sometimes need to manually fly the aircraft; in such cases, some communications, navigation, or systems tasks that the captain might normally have performed (e.g., normal checklists) may be temporarily assigned to the automation and/or the ground operator.

6. CONCLUSION

A framework has been presented for the development of an SPO ConOps by outlining options for key dimensions of the ConOps design space. First, a taxonomy of operating conditions was defined, spanning the dimensions of pilot condition and flight condition. Next, function allocation among various types of human operators was discussed, as well some candidate structures for ground operator units and the nature of services their operator positions would provide to the captain. Then, an options space was examined, with dimensions spanning the number of air-ground operators and the level of automation; minimizing the total number of operators does not necessarily provide the most cost-effective solution. Finally, requirements of advanced cockpit automation were outlined. Taken together, the above material sheds light on the roles/responsibilities of the various air and ground operator positions as well as the tools required to perform their tasks and collaborate with each other.

The SPO ConOps framework presented in this work is being used to guide the design of NASA's human-in-the-loop simulation studies; a recently completed study is reported in Ref. 6 and follow-on studies are in various stages of planning/execution. The results of these operational studies, along with cost-benefit analyses, will be used to develop an SPO ConOps meeting the requirements that it be technologically feasible, yield economic benefits, and provide a level of safety no less than conventional two-pilot operations.

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