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Enabling Single-Pilot Operations technological and operative scenarios: a state-of-the-art review with possible cues

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Abstract

Both financial and operational reasons have been given emphasis to the implementation of Single-Pilot Operations in commercial aviation. SPO will involve replacing the first officer with integrated cockpit assistants and support ground stations. This review aims to provide an overview of SPO through a classification of the specific areas of interest. Enabling SPO will require designers to re-modulate the human-automation interface according to the new allocation of functions in the flight deck. However, while technological issues are expected to be overcome in the next future, major attention should be paid on the human factor side.

1. Introduction

Since the early days of aviation, cockpit operations have undergone significant changes. The evolution of airliners has resulted in a gradual reduction in the number of crew members thanks to improvements in avionics and communication technologies. The personnel on board decreased from 5 to 3, and then to 2, as the flight engineer, navigator, and radio operator were replaced by the new glass-cockpit functionalities. To date, this number has not yet been reduced, even though the ongoing advances in systems reliability. The interest in Single-Pilot Operations (SPO), in fact, has only emerged recently within the commercial airline industry. The objective will be to assess robust solutions that can reallocate the first officer duties to reliable and automated subsystems and/or ground support operators. This attraction to SPO is basically driven by the challenges that modern aviation is expected to face, including the projected shortage of qualified pilots[51] and the increasing[27] air traffic (Figure 1). Considering this, some companies are working to prepare for the transition to SPO, which has the potential to produce significant long-term cost[4] savings. To date, in fact, a great number of experts agree in evaluating this change as an economic source of benefit. A study conducted by the Union Bank of Switzerland (UBS), for example, showed that by introducing SPO in commercial aviation, airlines worldwide would save USD 15 billions[38] in operating costs in the long term. However, despite these potential benefits, there is an ongoing debate about safety and Human Factors, and the technical, operational, and commercial feasibility of SPO has yet to be demonstrated. A less troubled development process is being experienced, instead, for the so-called extended Minimum-Crew Operations (eMCO) concept, which is based upon the improvement of extant designs where SPO will be just restricted to the cruise phase of flight (e.g. long-haul, transcontinental flights). Since the lack of the redundant first officer cross-checking function, one of the primary challenges for SPO would be to assess, as well to predict, any high workload situation for the single pilot in order to preserve his or her mental state on the mission plan and correctly manage sudden incapacitation episodes. In addition, since automation will take over some of the tasks of the co-pilot, it is necessary to design a suitable human-machine interface (HMI) that would be able to adapt to the operator's mental state. Other challenges could be generally linked to operations, communication procedures and processes, as well as to pilot/crew training requirements and systems integrity. The transition to Single-Pilot Operations will also necessitate a thorough revision of certification paradigms, taking into account the shift from deliberative/reactive systems to mixed autonomy systems that can be scaled according to operational conditions.

Currently, a great deal of effort is being made to evaluate the operational potential of some new flight aiding systems, which can be employed as a means to fulfill the new requirements imposed by the SPO. So-called Digital Flight Assistant (DFA) concepts of operation are currently being investigated at academic and industrial level in order to reduce the flight deck complexity and support the pilot during stressful decision-making processes, including those that can lead to an incapacitation. This system would generally be intended to perform a task or sensor-based real-time assessment of the pilot's cognitive state to provide specific alerts to prevent states of confusion or loss of awareness.

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Artificial Intelligence (AI)-based subsystems are particularly promising for these purposes; however, they introduce complex considerations regarding ethics, data transparency, and data governance. Therefore, given this framework, it is generally understood that contributing to the transition to SPO in commercial aviation requires a multidisciplinary approach that encompasses technical, economic/legal, social acceptance, and societal issues.

The purpose of this paper is to provide the reader with a review of the literature on the main class of concepts that are directly or indirectly related to the main topic of Single-Pilot Operations. The paper offers a broad overview of the current developments and trends in academic research concerning SPO, which has been proposed through a classification into different subtopics. This review aims to gain more insights into areas of interests that are mostly fragmented at the subsystem level, also establishing potential interrelationships within them. Overall, the paper is structured into four subsections according to the following areas: Operations, Cognitive Human-Aircraft Interfaces, Digital Flight Assistants, Certification and Communications. It was also useful to reorder knowledge in the literature to recognize that the major issues for a future implementation of a commercial aviation SPO would basically not regard technical progress, but rather that concerning operational issues. The paper selection for this work is not exhaustive for each subtopic, and a remind to more relevant and systematic literature reviews[24,62] are recommended.

2. Operations

The field of Single-Pilot Operations has traditionally been limited to General Aviation (GA) and military jet aircraft. However, there has been recent interest in extending SPO to include Very Light Jets (VLJs), which could provide valuable data for designing systems also for commercial airliners. Previous studies, such as Vu's[69] , have provided an overview of different single-pilot mission concepts that have been discussed in recent years, without identifying none of them as clearly superior. A similar conclusion was also stressed by Harris[24] who stated that "designing and building the aircraft may be the easy part: operating will be the challenge". The transition to SPO can be approached through two slightly different strategies: major operators' ground support or enhanced on-board automation. According to the first strategy, the single-crew aircraft is considered to be part of a wider system that accounts for a ground-based operator acting as a remote "second pilot" for real time engineering support to the cockpit. Any airliner, however, even with plenty of autonomous systems, shall require increased ground personnel to provide the necessary support for SPO, leading to a need for better coordination of roles. A first distinction involved the concepts of dedicated and distributed assistance[4] (Figure 1), which means that the same operator on the ground might be in charge of taking the flight controls of a single or multiple aircraft at a time. The NASA Single-Pilot Operations Technical Interchange Meeting[16] in 2012 provided a comprehensive discussion on different ground-assisted concept of operations, resulting in closer definitions for the roles of ground operators:

- **Hybrid Ground Operators**: These operators should undertake dispatch and support to multiple aircrafts in a nominal condition; a dedicated 1:1 support has to be provided just to aircrafts facing non-normal or emergency situations.
- **Specialised Operators**: This role could be further divided into Ground Associates and Ground Pilots, which are responsible for normal dispatch duties and specialized support, respectively.

To date, none of the aforementioned proposals has yet been indicated as the best choice for SPO, given that a realistic concern is addressed to complementary and economic aspects (e.g. the ratio of ground operators to pilots) that are still unsolved. Asokan[2] conducted a comparison of different high-level architectures, evaluating the trade-off between cost and safety. The author concluded that, when moving to SPO, benefits and costs generally depend on the class of aircraft (e.g. widebodies, narrowbodies, and regional jets), and the balance between automation and the number of crew members required on the ground to execute the flight. Regional carriers, for example, will greatly benefit of the reduction to a single-pilot crew, since estimation agree[22] that as much as 35 % of the total operating cost for flights travelling less than 200 nautical miles and carrying less than 50 passengers is due to the cost of the crew. The dedicated assistance paradigm was clearly found to be the most expensive one when employed for the entire duration of the flight, so a specific assistance would be worth it just for restricted time windows. Relying on the Harbour Pilot (HP)[33] concept would be a solution in that regard. The HP is the ground operator who would be responsible for assisting single-pilot aircraft during departures and arrivals in specific and complex flight areas, such as airports and their surroundings. According to Koltz's[33] research, the assessment of Harbor Pilot's feasibility from the ground operators' cognitive workload perspective was positive. However, implementing this concept can involve substantial resources in terms of costs and procedures. Some pilots, in fact, expressed concerns about technological challenges and the necessity of additional tools to prevent miscommunications in information exchange.

At a barely task level, the dispatchers/ground officers are in fact engaged as much as pilots whenever there are concussive flight phases. Their role involves skills such as perception, attention, memory, situation awareness, and

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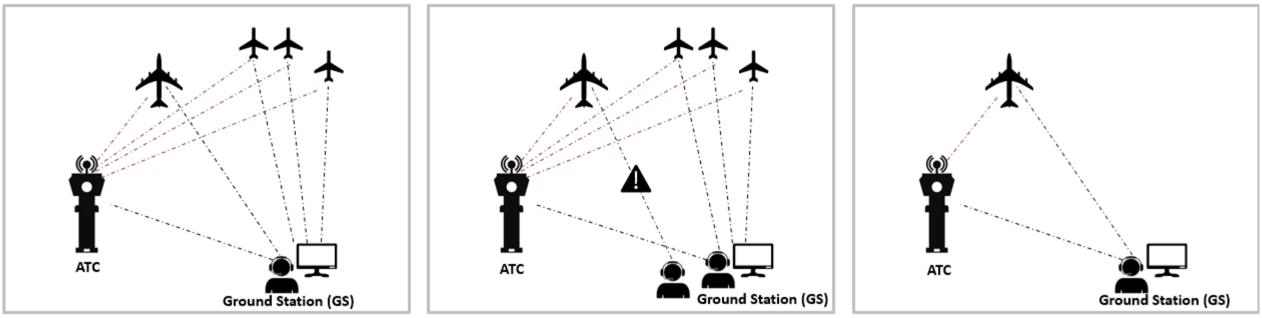
decision-making capabilities within a multitasking environment,[50] so that a non-negligible part of the SPO implementation will also depend on assessing the best condition as possible for these new controlling workers on the ground. According to the recent conceptual framework proposed in a paper within the SAFELAND[47] research project, each major phase (take-off, cruise and landing) should involve a different ground station with a variable number of operators. Regarding this, an essential aspect to effectively manage during Single Pilot Operations is the handover process between different ground stations, which can lead to an abrupt loss of aircraft control for both the pilot and ground operators responsible for taking over. The same contribution addresses the issue and suggests basic procedures for transferring control from the air to the ground and between different ground stations in the event of pilot incapacitation. To ensure efficient handovers, the framework emphasizes the need to appropriately allocate roles and separate them according to the specific flight phase. This approach aims to minimize confusion in flight management tasks, regardless of the associated costs of employing a larger workforce. The framework recommends that each operator be given sufficient time to familiarize themselves with the flight's progress and overall situation before assuming full control. Naturally, further research is necessary to address the challenges and obstacles associated with these concepts, particularly with the anticipated integration of Remotely Piloted Aircraft Systems (RPAS) in non-segregated airspaces.



(a) Distributed Assistance, Nominal. (b) Distributed Assistance, Non-Nominal. (c) Dedicated Assistance.

Figure 1: Schematic comparison between the Distributed and Dedicated Assistance approaches involving operators in a specific SPO-oriented Ground Station.

2.1 Organisational aspects

The proposed solutions would require significant procedural changes to accommodate scenarios in which single and dual pilot flights can be operated simultaneously and with minimal resources. SPO aircraft, in fact, would be at the core of a broader sociotechnical system, which requires task redistribution and the establishment of new roles and formal responsibilities in flight management[68] . The distributed assistance approach has shown greater potential for certification, while the dedicated one is challenged by the need for specialized training and certifications for ground officers. Then, a post-accident reanalysis evaluation study by Harris[23] focused on Harbor Pilots and indicated that a high amount of personnel would be required to support departures and arrivals for large, low-cost airlines. To minimize costs, national and international aviation providers should try to leverage existing infrastructure features rather than embarking on complete rebuilding efforts. The re-allocation of tasks, anyway, will also regard the predicted increase in the amount of automated systems on-board. Various methods[7,25,41,65] have been employed to explore design options for the allocation of functions in SPO, most of which are based upon Cognitive Task Analyses (CTA) for exploring how operators' cognitive processes come into play during task performance. Each technique is expected to help designers in different ways with the identification of the cognitive demands that would be associated with each task, so as to make new functional allocations between single-pilot flight agents (automation and humans). Notable examples of task decomposition within an approach-and-landing scenarios have been achieved using simple spreadsheets[10] or specialized platforms.[72] Generally, task descriptions follow a structured hierarchical approach[37] to specify all potential logical constraints and the relationships between them. A more recent scheme called Operational Event Sequence Diagrams (OESD)[25] aimed, instead, to emphasize the timing and sequencing of the activities. This approach, in fact, would not only ease the reconfiguration of normal dual-pilot tasks to suit SPO but also the identification of those tasks that may no longer be necessary in the transition. Validation processes for these techniques have primarily involved intensive briefing sessions with subject matter experts, supported by data acquisition sessions with pilots. These sessions may include video and audio recordings, discussion groups, and surveys. Recent contributions, such as

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the one by Li[38] , introduced new tools to precisely list each agent's function and employ graphical and mathematical procedures to evaluate the level of interaction, including frequency associations, closeness, farness, and betweenness.

3. Cognitive Human-Aircraft Interface

One of the remaining options discussed in the 2012 Interchange Meeting on SPO involved replacing the first officer role with increasingly sophisticated on-board automated systems. This solution, by the way, had already been deemed within the previous NASA literature[6,66] that aimed to support the development of intelligent cockpit assistants. Therefore, an emphasis was being placed on increasing automation in the active research in aviation, thinking of it as a means of simplifying the function allocation for both single pilots and ground operators. However, the more automation gets involved in a shared decision-process with humans, the more their mutual interactions need to be detailed to avoid risks such as automation complacency, cognitive overload or underload. To facilitate a reliable collaboration between agents on board, a Human-Machine Interface (HMI) will therefore be necessary. The HMI should enable adaptive interface functionalities that can minimize the impact of pilot errors through adjustable levels of automation. Since full-automated scenarios cannot be, to date, a viable choice, there is still a desire for some lighter remote support from the ground. This section explores the advantages and disadvantages of automation in aviation, highlighting the potential role of these systems on the flight deck of a single-pilot mission. Additionally, a historical overview of proposed taxonomies for categorizing levels of automation is provided.

3.1 Automation, Adaptive Automation and Levels of Automation (LoA)

Automation might be defined as the execution by a machine agent (typically a computer) of a function that was previously carried out by a human[54] . The Oxford English Dictionary defines it, by extension, as "the use of electronic or mechanical devices to replace human labor". Early attempts to determine whether humans or machines were better suited for specific functions can be traced back to Fitts' MABA-MABA list (Men Are Better At - Machines Are Better At). This list initially concluded that humans should focus more on inductive and judicious reasoning while leaving mechanical or precise activities to machines. However, the line between the two has become increasingly blurred with the passing of time. With the transition to SPO, in fact, a new paradigm should be considered that places users at the center of a system design process. According to the ISO definition, this so-called Human-Centered Design *"aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques. This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility, and sustainability; and counteracts possible adverse effects of use on human health, safety, and performance."* Automation gained significant attention in the 1970s and 1980s due to its potential for increasing profits and speeding up industrial production to maximize efficiency. The aviation sector also received much interest in this regard when the so-called glass-cockpit concept was introduced, which led to the replacement of flight engineers with automation. The sector really improved in that time, but some warnings came out the same when some systems ended up to reduce the pilots' workload in situations when it was already low and increased it when it was high, instead of the opposite. Two main design indications still emerged as crucial aspects for the implementation of a shared work environment, regardless of the specific application. Firstly, the automation should enable the operator to understand its actions, and secondly, it should allow the operator to intervene easily at any moment. Despite the progress which have been made until now, it is evident that a human supervisory would still be needed within SPO, and that users are required to act more like managers rather than pilots. Numerous studies conducted in the 1990s, such as those by Parasuraman[53] and Chambers[14] , aimed to provide empirical evidence of the human role in the use of automation. Brown[9] spanned the literature for three decades to investigate the lesson learned about the effect of automation on Human Factors in aviation, coming out to pinpoint the loss of awareness of automation as one of the most remarkable concerns when talking about HMIs. Post-accident investigations often have revealed scenarios to prove how much advance in automation can also be a troublemaker. Complacency is described, in fact, as the "failure to be vigilant in supervising automation prior to the automation failure"[71] , and it has been reported as a possible cause for the attentional tunneling phenomenon. The so-called out-of-the-loop syndrome, instead, was described as the failing in continuously recognizing what the automation is doing or not. This can generally occur when users excessively focus on instrumentation while neglecting their physical surroundings. The survey by Parasuraman[54] provides valuable strategies for managing automation-related issues and emphasizes the need to consider the human element when introducing more automation into a process. Operators should try to avoid what the author recognized as "misuse" and "disuse" scenarios, as well as the complete abuse of those systems' capabilities. As far as the automation potentialities keep improving, humans remain mostly unchanged by contrast, and it is why an increasing complexity might be at risk of becoming a potential bottleneck for operators. A possible cognitive overhead in managing an automated subsystem could, in fact, even outweigh its potential benefits, so much to let it become very less attractive.

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The current goal is to enhance research on advanced automation under human supervision as the basis for planned autonomous solutions that will instead rely heavily on Artificial Intelligence. As often acknowledged by insiders, technology challenges are not, to date, the primary obstacle to the practical implementation of SPO. Manufacturers and avionic suppliers, in fact, are making progress in the development of SPO, even outside of the commercial aviation sector.[17] Additionally, there is a wide range of AI-based algorithms available for integration into normal flight operations, even for single pilot cases. Rather than simply automating a function, designers today should focus on determining to what extent to do so. The goal would be, in fact, to fully capitalize on the potential benefits offered by automated systems and investigate for the reasons why an aid should be used and what would be the conditions, instead, to let it be unused. Some research around the topic of managing automation control modes was already addressed by Kirlik[31] , who analyzed some possible optimal policies for using the autopilot in both single and dual crew conditions. The author demonstrated how aid-design and flight task context factors can interact in complex ways to affect policies for using specific automated systems with strong differences between individuals. Such contribution paved the way for a general aspect which is currently under research, namely the creation of a structured pattern for assessing how much automation involvement is really needed into a process. According to the most recent studies, the automation amount shall be assumed to dynamically vary across a continuous set of levels ranging between the two extremes of "no external aid from devices" and "full autonomous systems". A more balanced automation utilization is instead placed in the middle. Some works around the literature[18,41] proved the adaptive automation criterion as a feasible way to mitigate the human decision-making performance. Classifications into levels should adhere to specific taxonomies that associate qualitative descriptors with numerical levels. Sheridan[63] proposed a 10-point scale based on automation applied to decision-making moments within human information processing. A subsequent analysis by Parasuraman[56] outlined a two-variable taxonomy for the Air Traffic Management (ATM) activities having the level of automation on one variable and processing stages on the other, the latters consisting of: a) information acquisition; b) information analysis; c) decision and action selection and d) action implementation. According to the author, these stages might be separately automated following considerations about the consequences that each of them may have on human performance. Another detailed taxonomy for ATM activities was shown by Save[61] , whose proposal can be transferred even to those different domains where the design of a pilot-machine interface is needed.

Adaptive automation[55] involves assessing the extent to which direct control authority over a task is shifted between humans and automation. As all the automated systems, however, an adaptive automation will require an allocation authority agent (human or not) to act as a supervisor in an outer loop. Supervisory control generally boils down to changing parameters of elements in the inner loop, or to executing simulations that will inform decisions to change parameters (e.g. setting an alternate airport into the flight management computer after an adverse weather report). Of course, all these parameter changes can be up to a human or to a further automated agent (this case is recognized as adaptive control engineering). Despite the prevalent use of automation, the fundamental rule for designing adaptive associate systems remains to allow the pilot to supervise the cockpit without intervention unless it is a last resort. Such a distinguishing paradigm has been adopted within the research groups at Bundeswehr University of Munchen. An heterarchical, cooperative automation was, in fact, introduced with Brand[8] to act as a human partner within the framework of cognitive agents. The operator is responsible for engaging, supervising, and disengaging the aiding system and retains the ability for direct manual control when appropriate. Automation assumes control only when the cost of failure can be too high, e.g. in case of a pilot incapacitation.

3.2 Flight Deck Evolution for SPO

The civil aircraft flight decks have already gone through an extensive bunch of modifications, in the past, when dials and gauges were replaced with computerized displays. What is now termed “the glass cockpit” was introduced by Airbus with the A320 family in the mid-1980s, followed by the 747 and MD-11 in the early 1990s. These renewals were also the cause of an exponential increase in safety that has led, today, the airliners to be the most reliable means of transportation in the world. The information was presented on screens in the cockpit with more intuitive interfaces to provide the crew with precise and quick access to data. The greater the requirements on safety, instrumentation redundancy or the access to measurable data during flight, the more complex the flight deck interface can become. Modern pilots are in fact usually required to manage too many types of information coming from different sources at the same time. Such an effort would be unacceptably high in case of a single-piloted flight. Authors, for example Chandler[15] , suggest that pilots will perform better with single integrated sources of information, so that another renewal in the cockpit instrumentation panels and overall architecture could be faced in the next future. Thomas[67] has provided insights into the state-of-the-art and emerging control devices for managing the interaction with automation, both for ground and airborne personnel. A remarkable interest went for the implementation of head-mounted displays in the last decades, as a means to improve the control of the aircrafts activities through the concurrent scan of instrument data and the outside scene. However, there have been reports of perceptual and cognitive issues associated with their

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use, such as attentional tunneling or cognitive capture.[21,29] Gesture-based control remains, instead, a less researched domain. Voice control and Automatic Speech Recognition (ASR) devices can be, on the contrary, highly relevant for SPO as they aim to restore similarity with conventional on-board procedures such as briefings and checklist approvals[5]
.

Current research is focusing on smart adaptive subsystems that can be activated based on a quantified measurement of the operator's cognitive workload. An ideal cockpit for SPO should, in fact, just shed light on the information which is relevant to the detected context. Concerning industry, there are notable recent examples worth mentioning. One of them is the Anthem cockpit developed by Honeywell Aerospace, which stands out for its implementation of cloud-native communications, navigation, and surveillance systems. Instead of relying on conventional computers and cabinets located in the aircraft's electrical equipment bay, all the processing tasks can be, in fact, integrated directly into its intelligent displays. Unconventional interaction methods are being explored nowadays to create more intuitive interfaces, such as eye and gaze-tracking techniques, gesture or voice controls, or haptic-feedback control devices. Calhoun[11] and Merchant[49] , for example, conducted experimental investigations on the use of eye tracking for activating controls and function switches. The workload-adaptive associate system introduced with the Institute of Flight Systems (IFS) research groups[8,26] was built, instead, upon a non-invasive video-based system which aim was to assess the pilot current activity by relying on a collection of gaze-driven accumulated pixel coordinates. The cognitive human-aircraft interface modelling presented by Liu[41] also employs eye-tracking for a parameter-based workload estimation. Yu,[75] then, describes a situational awareness enhancing system that consists of measuring the pilot's workload through the real-time detection of physiological parameters and making workload predictions to adjust the supporting automation in advance. To enable this predictive strategy, Yu proposes: a) a tacit knowledge mining system, which employs gaze tracking to extract expert pilots' visual cognitive patterns and tunes the displays in a more efficient way; b) an explicit expert knowledge mining system, which simply collects pilots' considerations and makes them as coded behavioral rules.

4. Digital Flight Assistants

Recent literature on Single-Pilot Operations has focused on exploring the feasibility of a Digital Flight Assistant (DFA), that would have the dual role of managing new automation systems on board and providing support to the pilot during high workload phases. The Digital Flight Assistant aims to leverage advanced automation technologies to assist the pilot in handling the increasing complexity of modern aircraft systems. By assuming some of the responsibilities traditionally held by a co-pilot or flight engineer, this assistant can alleviate the cognitive load on the pilot and improve operational efficiency. Overall, the aim of a DFA will be to recover and manage the control of an aircraft in case of a pilot incapacitation, both directly or by letting a ground operator to intervene. Despite it seems an intuitive one, the construct of mental workload remains to date surprisingly difficult to define, with no universal agreement that has been reached, yet. Authors[64,74] generally concur that mental workload refers to the level of attentional resources required to meet both objective and subjective performance criteria, which may be mediated by task demands, external support, and past experience. To develop a comprehensive understanding of workload, a specific metric needs to be developed and selected for its measurement, as this will be the factor by which the automation intervention on the aircraft should be adjusted. Currently, there are several improved methods for estimating workload: a) subjective assessments or questionnaire-based feedback strategies such as rating scales or structured interviews (e.g. NASA TLX, Subjective Workload Assessment Technique (SWAT)); b) task-based workload models, which basically combine all related task demand together with a measure of their degree of interference; c) psychophysiological-based measurements, which involves correlating key pilot's biological signals with performance decrements. While associating workload with task loads has yielded positive results, all the recent advance in wearable and non-wearable sensor networks research is paving the way to develop a real-time pilot's estimator which would be triggered and alerted in case of a deviation with respect to nominal conditions. Apart from the questionnaire-based one, the remaining two approaches are described in the followings.

4.1 Task-based Workload models and Multiple Resources

The aeronautic environment is recognized as a complex one that often requires individuals to perform multiple tasks simultaneously. Workload models can be classified according to the assumption they make concerning time-sharing performance: a) the single channel[39] model assumes that the pilot is capable of one task at a time; b) the single resource model[28] acknowledges that concurrent task performance is possible but draws from a single and limited pool of mental resources; c) the multiple resource model[70] instead proposes that demands may also be offloaded by distributing tasks across resources. According to the latter, individuals possess a sort of limited capacity central processor that can allocate its involvement to different channels as different are the tasks it has to accomplish. Wickens' article "Multiple

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Resources and Performance Prediction"[70] gave a significant contribution to research on resource management in multi-tasking environments, asserting that people have a limited set of resources available for mental processes. All those resources can be modeled with a set of dichotomous channels for what concerns each stage of mental processing, e.g. perception, cognition and response (Figure 2).

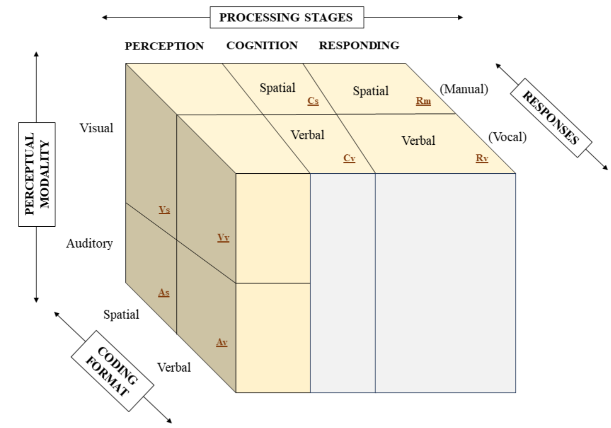

Figure 2: Multiple-Resource Model visualization as proposed by Wickens[70] .

A further model was proposed by the same author for computing the resource interference between concurrent tasks, so that this estimation can add a contribution for the workload determination beyond that already associated to the demand level of the task. A similar framework is employed in the workload-adaptive associate system proposed by Brand,[8] as well in the Military Rotorcraft Associate (MiRA)[45,46] for helicopters. Another notable reference for workload modelling is Sarno[60] , that provided a detailed description of three prominent examples:

- **Time Line Analysis and Prediction (TLAP)** Model - This model estimates performance based on a time line approach. Empirically, it is observed that performance tends to decline when the time required for a task exceeds 80% of the pre-allocated time. Therefore, workload can be calculated as the ratio of the time required to the available time. This model does not make any assumption about task competition across channels.

- **Visual Auditory Cognitive and Psychomotor (VACP)** Model - The VACP model considers separate workload components (or channels), which are the visual, auditory, cognitive, and psychomotor one (manual and voice responding). For all these components, a vector of demand values has to be assigned according to evaluation scales criteria created by subject matter experts (validity has to be continuously proven). The average workload can be computed by summing the demands within each component for all the tasks performed at a given time.

- **WL index (W/INDEX) Model** - The WL index (W/INDEX) model is heavily influenced by the multiple resources theory. This model explicitly calculates task interference, assuming that interference is proportional to mental workload. Task interference occurs when tasks involve overlapping resources. The W/INDEX model requires a matrix of resource-conflict coefficients, which determines the level of penalties between tasks.

A good workload model should be able to make predictions that are highly correlated with empirical measures of performance. The study from Sarno, indeed, employed performance data to evaluate the predictive power of the three models. Subjects were required to simulate a flight task while performing few side activities with varying difficulty and resources involved. All the three models did a relatively good job in predicting the degree of multitask interference. The most interesting aspect about this paper was to recognize that the most general way to define the interference between some tasks is by setting a score, such that the interference would be greater as more numerous are the different resource channels which are employed at the same time.

4.2 Pilot Health Monitoring

In recent times, significant efforts have been dedicated to exploring the relationship between workload and human physiological signals, as this can have the potential to reduce incidents and accidents related to pilot incapacitation. A structured sorting of the existing bio-signal monitoring systems for aviation can be found in the systematic literature review on SPO by Schmid[62] as well as in specific publications on sensors such as the review of Pongsakornsathien[57] . Interested readers are encouraged to refer to these publications.

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Several wearable devices have been already developed in the medical field[43] to effectively measure physiological quantities such as heart rate, breathing rate, blood pressure, blink rate, eye movements, or even facial expressions. Despite the attention that aviation industry has already dedicated to many of these sensors due to their potential for detecting pilot stress levels, Pilot Monitoring research field is still at the beginning and more efforts will be needed to assess robust correlation models that can be tested in real aircraft environments. A major aspect will be to take into account that stress is a multifaceted construct which normally gets influenced by various individual and situational factors. Here are some notable wearable sensors which are eligible for stress detection in aviation:

- **Electrocardiography (ECG) Sensors**: ECG sensors measure the electrical activity of the heart, providing insights into heart rate variability (HRV) and cardiac response. Changes in HRV can indicate stress levels[12] and physiological arousal.
- **Electrodermal Activity (EDA) Sensors**: EDA sensors, also known as galvanic skin response sensors, measure changes in the skin's electrical conductance, which reflects sweat gland activity. Increased EDA levels are associated with sympathetic nervous system activation, indicating stress[42] or emotional responses.
- **Electromyography (EMG) Sensors**: EMG sensors detect muscle activity and can identify patterns of muscle tension or relaxation. Increased muscle tension in certain areas, such as the forehead or jaw, may indicate stress or anxiety.
- **Accelerometers**: Accelerometers measure motion and acceleration in multiple directions. They can capture physical activity, body movement, and postural changes associated with stress or fatigue.
- **Photoplethysmography (PPG) Sensors**: PPG sensors use light to measure changes in blood volume and blood flow. They can provide information about heart rate, blood pressure, and arterial stiffness, which are associated with stress responses.
- **functional Near-Infrared Spectroscopy (fNIRS) Sensors**: fNIRS employs near-infrared light to detect fluctuations in oxygenated hemoglobin and deoxygenated hemoglobin concentrations in the prefrontal cortex, providing an indirect measurement of brain activity.
- **Electroencephalography (EEG) Sensors**: EEG sensors measure brainwave activity by detecting electrical signals from the scalp. They can assess cognitive states, mental workload, and emotional responses, including stress levels.

Concerning EEG, for example, an increase in the cognitive workload is often associated with higher theta-band power and lower alpha-band power.[58,59] Information for the temporal, spectral and statistical domains can be extracted from the alpha-to-theta and theta-to-alpha EEG band ratios. Aricò[1] developed an online Mental Workload classifier based on EEG signals recorded from scalp electrodes. Such method also takes into consideration the EEG theta and alpha rhythms and introduces an automatic stop in a standard classifier method that interrupts the process of features selection when an optimal number is reached. Some other parameters can be introduced in brain activity detection; for example, within the adaptive system proposed by Dorneich[18] the author used the event-related potential (ERP) P300, which is an EEG-evoked response occurring when unexpected stimuli occur. Apart from the list above, also the eyes-related activity, involving fixations, blink rate or saccades for instance, can be associated with workload measurements. Specific glasses or commercial camera-based video recording systems need to be employed for this purpose. An example was shown by McDuff[48] that used a five band digital camera to detect cognitive stress throughout the observation of pilots' facial landmarks, or by Honecker application[26] that involved the use of multi-camera systems for the recognition of visual areas of interest based on gaze tracking.

Generally speaking, to enable these bio-signals detection, the sensors are required to provide real-time monitoring without causing too much of discomfort to the pilot, as it is for those compact wearable sensors integrated in consumer electronics. Various efficient devices have been developed for this purpose, including energy-harvesting arm devices[52] or smart shirts. A wireless, fully wearable wristband was reported instead by Maiolo[44] for the pilot's cardiac activity detection. It is worth noticing that the field of wearable sensors for stress detection in aviation is still evolving and facing several challenges that need to be addressed. This will require collaboration among aviation regulatory bodies, researchers, manufacturers, and aviation stakeholders. Some of these challenges and the main features that these systems should reach are listed below:

- **Reliability and Accuracy**: Wearable sensors need to provide reliable and accurate measurements to ensure the validity of the collected data. The sensors must be capable of delivering consistent and precise readings under various environmental conditions and during different phases of flight.

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- **Sensor Integration and Compatibility**: Integrating wearable sensors into existing pilot equipment and cockpit systems can be complex. Ensuring compatibility with the aircraft's avionics and data management systems is crucial. Seamless integration requires careful consideration of data transmission, connectivity, power supply, and data synchronization.

- **Standardization and Validation**: Establishing standardized protocols and validation procedures for wearable sensors in the aviation industry is essential. Consistent measurement methodologies, calibration procedures, and data analysis techniques need to be developed and agreed upon to ensure interoperability and comparability across different sensor types and manufacturers.

- **Data Privacy and Security**: Collecting physiological data from pilots raises concerns about data privacy and security. Strict protocols and encryption methods must be in place.

- **User Acceptance and Comfort**: Wearable sensors should not impede pilots' comfort, mobility, or performance. They should be ergonomic, lightweight, and non-intrusive to minimize distractions and maintain optimal pilot functioning.

- **Regulatory Compliance**: Introduction of new technologies - including wearable sensors - into the aviation industry requires adherence to regulatory standards and certifications.

Another aspect to take a look at is the management of noise and motion artifacts, especially when passing from laboratory conditions to a real-time application. A sensor network should be adopted to avoid contaminated signals. Different approaches might be chosen for doing that, as stated by Pongsakornsathien[57] : a) independently estimating cognitive states from each sensor and then fusing these estimated; b) cognitive state estimation based on a fused pool of extracted features from each sensors, c) using data from one or more sensor to extract more/different information from another sensor and/or for sanity checks. Up to the current progresses, approach (A) would be the less robust as the individual extracted features can be caused by multiple combinations of cognitive states. Approach (B) would be definitely be more reliable as the simultaneous observation of different features mitigates the ambiguity in cognitive state estimation, that is the base of data fusion techniques. Approach (C) is, instead, requiring a much deeper understanding of neurophysiological processes. Actually, an important topic which remains open is the optimal choice of the physiological indicators for the computation of mental workload. The pilot-aircraft interface proposed by Liu[41] provides an easy-to-use mathematical framework of real-time cognitive states estimation based on a selected portion of physiological measurements, to which the author also adds environmental and operative data.

4.3 Artificial Intelligence in Aviation

There is still little contribution from the literature regarding a possible analytical framework that describes the relationships between psychophysiological parameters and mental stressors. While the combined use of different sensor types in a network can enhance the reliability and accuracy of estimating cognitive states, individual differences remain a significant factor in introducing uncertainties. Certain measurements can be, in fact, highly susceptible to daily variations in individual physiology or rely on the user's experience level. According to some research, even cultural considerations shall be considered, as individuals with various educational backgrounds may react differently to external stimuli[9] . Constructing a person-independent classifier would therefore be ideal. Fuzzy clustering and fuzzy identification techniques have demonstrated potential in adapting systems parameters to individual users based on their daily physiological states, as seen in the Kumar's experimental study[34] on HRV. On the other hand, the development of artificial neural networks has been recently offering a very interesting complementary approach. Laine,[36] for example, investigated the feasibility of a single model based on Machine Learning in order to classify mental workload across different subjects. More recently, instead, a human subject-specific recognizer based on Deep Learning (DL) principles has been proposed[73] by Yang, too. With such contributions, research proved that the use of AI in aviation can be an enabler for new subsystems for Single-Pilot Operations. AI can also provide valuable support to the crew by delivering critical situation forecasts, facilitating faster problem-solving through optimization techniques, and reducing the workload of air traffic control operators through improved predictions of traffic behavior. A catalogue of the current AI-based solutions for aviation was collected in the "Fly AI Report" compiled by the European Aviation High Level Group on AI.

AI basically defines the boundary between automated and autonomous systems. Unlike simply automated, an autonomous system has the ability to determine a course of action from various alternatives and be adaptive to situations which have not been predetermined. SPO could be considered exactly in the middle of these two opposing concepts, since the requirements ask for a "scalable" autonomy that can namely adjust its level of authority spanning from being a simple automated system and an autonomous one, if needed. The AI usage in aviation was already envisioned in

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2000s with still not so ambitious projects; one was named, for example, CAMMI[30] (Cognitive Adaptive Man-Machine Interface). Then, much has changed in just over 10 years, as in 2020, for instance, the Airbus demonstrator system called Autonomous Taxi, Take-Off and Landing (ATTOL) was successfully able to fly an entire mission with the support of AI and computer vision algorithms. Presently, the development of an AI system that integrates a DFA is widely acknowledged as one of the most arduous endeavors. In reality, achieving effective training for such assistants can pose challenges due to the complexities associated with accessing authentic flight data, primarily due to security and privacy concerns. Thus, it becomes crucial to establish a common legal framework that unifies government-held data and to implement policies enabling open access to publicly funded research data.

Due to the limited availability of open data access, other training approaches for AIs have been employed. These include surveys, interviews with pilots, or utilizing video recordings from flight simulators. For example, within the HARVIS project (Human Aircraft Roadmap for Virtual Intelligent System), a machine learning-based DFA was developed and tested with such backup techniques. Scenarios involved a dynamic deviation in flight[3] or a go-around execution in the approach and landing segment following a non-stabilized[19] approach. Summing up, the expertise gained so far has led to a list of the general requirements that an AI-based aircraft aiding system should have: a) speech recognition capabilities for automatic briefing and checks,[5] b) ability to intuit when to interrupt the pilot in the decision-making process, c) independent monitoring of aircraft system states, either through computer vision or intelligent health and status monitoring systems, d) ability to recognize and interpret non-verbal communications from the pilot, e) error monitoring. e.g. timing of actions, missed communication, f) ability to take over flight control and potentially land the aircraft in extreme conditions, g) ability to inform the pilot about what the automated system is “thinking” including indications of what actions the automation may be about to perform. Currently, the attention is put on ensuring a regulated, mostly human-centric AI development in the aviation domain. The "EASA AI Roadmap" documents outline a comprehensive plan for a safe and reliable integration of AI in aviation. This roadmap includes a taxonomy which categorizes AI in three types of applications: human assistance (Level 1 AI), human-AI teaming (Level 2 AI), and advanced automation (Level 3 AI). The gradual implementation of AI applications for single-crew operations is projected over the next 10-15 years, encompassing both large commercial air transport and the air traffic management domain. The introduction of artificial intelligence in aviation poses additional challenges to authorities like EASA, as it would crate the need for ensuring staff competency to bridge the knowledge gap with industry experts, as well as for establishing rules to prevent the development of dangerous applications that may infringe upon human fundamental rights.

5. Regulation and Communications

The crucial step that the SPO development will have to face with is about regulations. A new regulatory approach to safety assurance will in fact be required to prove that commercial operations can be performed as safely with a single pilot as with two. Enabling the concept of Single-Pilot Operations will also change the criteria that lead the way of building a certification requirement. A great deal of the efforts that international players will have to make in posing new certifications is, in fact, directed towards the Human Factors aspects[24] . Also, given the complex organisational structure that SPO might involve for combined air-to-ground operations, the ground personnel should be enforced with a proper regulation, too. To this extent, the previous experience which has been already gained by international regulators for RPAS or SPO in general aviation and business jets might be an advantage. As said, several aspects can contribute to the settlement of a new regulatory framework for SPO, so that the approach which is currently being applied is trying to expand the existing dual-pilot dedicated certifications with the addition of specific guidelines for the single-pilot case. Under current regulations, for instance, all large commercial aircrafts should be flown with a minimum flight crew of two. According to FAR 25.1523 or FAR 25 Appendix D, such minimum is decided on the base of the perceived pilot workload, so as it will be the case also for an hypothetical SPO demonstration. One relevant document that can be cited is the CAA AC 91-11, which is an Advisory Circular from the Civil Aviation Authority in UK describing the standards and relative checklists for single pilots during IFR operations,[40] and showing up that the greatest contribution to flight safety can be achieved with a good pre-flight preparation. An active European Horizon Europe research project[20] led by NLR is, instead, currently investigating the feasibility of a Safety Risk Assessment Framework for extended Minimum Crew Operations (eMCO) or Single-Pilot Operations (SPO). Its aim is to assess the issues of the implementation of both in the EU regulatory by the next decade. EASA will consider these outcomes as one input to its rulemaking work to enable eMCO/SPO operations.

A review of the current certifications, acceptable means of compliance (AMC), guidance materials (GM) and recommended practises that are working towards an adaptation to SPO applications is given in the paper[40] by Lim. A table of summary reports all the useful indications on the official guidelines and documents held by international organizations. A further aspect that needs to be taken into account for enabling single-pilot procedures is about the amount of data that any virtual pilot assistant should manage and exchange with ground stations. Given the various

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physical spatial distribution of airliners' operators (including the single pilot and the dispatchers) the quality of the information which is transmitted would be different with respect to dual-crew operations. Hence, that could introduce new vulnerabilities in the system, that new kind of data encryption would be able to avoid. Encryption, though, can be problematic since countries have different laws governing its usage in their airspaces. Also, encryption generally introduces signal-transmission delays, or latency, which might be detrimental for the real-time sharing of data between aircrafts and ground stations. At the same time, due to the introduction of possibly AI-based systems on the flight deck, the overall aircraft can be subject to new kind of threats coming from outside. A so-called data poisoning occurs, for instance, when the attacker is able to access the model training dataset by injecting erroneous data and thus make it learning something it should not. A kind of infrastructure with a low latency, high bandwidth, securely encrypted and highly reliable data-link via satellite still does not exist. The reference by Carloni[13] performs, instead, a survey and an analysis of air-to-ground wireless channel models present in literature for providing recommendations to select and to apply them in budget-link computation.

Communication is also a matter of social issues inside the cockpit, since the lack of the first officer may lead the single pilot in confusion or in a boredom status. Speaking about standard flight conditions, a status of confusion is generally apparent for those pilots not being aware of what the other pilot is doing[35] . So, the physical separation between a single pilot and the remote-dispatcher who is in charge of taking control if there is the need, would much emphasize this aspect. When the other entity is an AI, things can change further. Past research has shown that humans are highly influenced by superficial aspects of the AI agents, such as their apparent gender, humanness, politeness, and personality, and that users from different technical or cultural,[32] or linguistic, backgrounds can have widely varying mental models of how AI systems work. One of the key drivers for the implementation of SPO in the future will be do the design with the continuous support of pilots' opinions. Once several experts are involved into this transition things can go better and trust in autonomous systems may be increased (people perception can negatively change if even pilots have doubts). Generally speaking, pilots like technology, and they are very careful to the preservation of safety. As this research shows, the first step is to ask pilots themselves, and have them involved at the core of the design of future autonomous systems.

6. Conclusions

Single-Pilot Operations are expected to offer cost efficiency and to address the challenges of the limited pilot supply in a growing aviation market. Based on the latest updated schedule outlined in the EASA AI-Roadmap, a feasible single-pilot solution for large commercial airliners and ATM operations is anticipated to be achieved by the mid-2030s. Much of the required technology is, indeed, currently under development or already available. Airbus, for instance, has identified their newly launched A350 Freighter as a potential candidate for this transition. However, some concerns have been raised by pilots' unions regarding the capability to manage safety issues with SPO and the social acceptance that these will have among individuals. Currently, the major obstacles to the development of SPO primarily stem from the Human Factor perspective. The challenge will lie, in fact, in ensuring the highest level of safety for passengers without imposing excessive workload on pilots in the process of adapting to new procedures and standards. The main objective of this review was to provide insights into the current state of research on SPO, doing this by taking different points of view across macro topics in the context of a very wide subject. Our goal was to select key areas of interest that can be further explored within the context of transitioning to SPO. Overall, this review served as a resource for gaining insights into topics that are mostly fragmented at the subsystem-level, with particular attention to identified current gaps or possible cues to keep work on. Enabling SPO will require significant changes in current operations, involving the establishment of new roles and responsibilities as well as the reconfiguration of existing ones. Automation will play a crucial role in this, as a reshape in the actual interfaces on the flight deck will be required to realize a space where the operators could be perfectly integrated with systems. One of the most interesting concept that is expected to emerge as a result of SPO is the so-called Digital Flight Assistant (DFA), which will support the single pilot based on his or her detected workload. Up to now, there are still few examples of workload-adaptive virtual assistants which could be found in the literature. An important research line was developed in Germany implying task-based adaptive strategies primarily in the context of military helicopters operations. There is also growing consensus regarding AI-based assistant concepts, even though their future evolution will depend on the accessibility of government-held data for training purposes and the future development of non-intrusive, efficient Pilot Monitoring techniques. Research is poor, instead, in the area of cockpit communication issues posed by SPO. The development of an infrastructure that provides low latency, high bandwidth, and highly reliable data-link via satellite remains a challenge. In summary, while technology-related challenges are expected to be overcome in the near future, the Human Factors design requirements will be the primary drivers for the successful implementation of SPO. This will also include the establishment of new certification specifications and standard procedures to ensure a not degraded level of safety.

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