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RESEARCH

Enabling Civil Single-Pilot Operations: A State-of-the-Art Review

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Abstract
Advanced avionics and automation technologies have significantly transformed cockpit operations, resulting in a gradual reduction of the crew members on-board. Single-pilot operations (SPO) concept is gaining significant attention in the aviation industry due to its potential for cost savings and to cope with the anticipated pilot shortage and the increasing air traffic demand. This paper conducts a scoping literature review on SPOs, serving as an initial step to map the scientific peer-reviewed content on the subject. The survey focuses on three thematic domains, which are, respectively, operations, automation, and the emerging field of digital and cognitive flight assistants. The methodology involved the use of Google Scholar and IEEE Xplore databases. Sources were selected adapting the search criteria to the proposed sub-topics and prioritizing either the most cited and recent contributions. The analysis of the literature reveals a growing body of work in the recent years. This review also highlights interest in the human-centered design for automation solutions which are responsive to cognitive and behavioral states of the pilot. While acknowledging the potential safety and operational challenges associated with SPOs and the pilot-automation cooperation, this work suggests that great research efforts should be made on the human factor and regulatory subjects to pave the way for a feasible and safe implementation of the single-pilot paradigm in commercial aviation.

Keywords Single-pilot operations · Digital flight assistant · Virtual pilot assistant · Pilot monitoring · Pilot assistance · Literature review

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 either in the avionics and communication technologies. The personnel on board decreased from 5 to 3, and then to 2, as the flight engineer, the navigator, and the radio operator were progressively replaced by the new glass-cockpit functionalities. As of now, the prevailing standard still adheres to a dual-crew setup, although the duties on-board are significantly changed with respect to the past, with most of them being automated. Aside from its predominant use in the military sector, the single-pilot operations (SPO) concept is garnering increasing interest in the civil aviation as well. This concept involves the operation of a commercial aircraft with only one pilot in the cockpit, supported by advanced on-board automation and/or, potentially, an additional dedicated ground flight crew which would likely complement the existing air traffic control (ATC) framework. With the absence of the First Officer (FO), all his or her roles should be redirected or potentially modified to be handled by automation. Changing towards single-pilot operations could result in a significant shift in cockpit dynamics, requiring the single pilot to undertake the entire flight duration in the role of the Pilot Flying (PF) without the ability to switch roles. Such situation contrasts with the common practice in dual-crew operations where crew members typically share equal PF and Pilot Monitoring (PM) duties.

Single-pilot operations is expected to offer significant long-term cost savings [1], giving a possible solution to both the projected shortage of qualified pilots [2] and the increasing [3] air traffic demand. Several experts agree in

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evaluating this change mainly as an economic source of benefit. A study conducted by the Union Bank of Switzerland (UBS), for instance, showed that introducing SPO for the airlines worldwide would save USD 15 billions [4] in operating costs. Similar considerations apply to the concept known of extended minimum-crew operations (eMCO), which is based upon the improvement of extant airborne designs for long-haul flights. Under this approach, two pilots would manage critical phases such as takeoffs and landings. A rest phase would instead be permitted for one of the pilots during the cruise. This strategy is designed to reduce both the physical and mental effort required to the crew and potentially increase the number of daily flights with the same crew configuration. On the other hand, the lack of interaction and coordination between the crew members would require new practice in training, making it necessary to modify some established crew resource management (CRM) techniques. Although the potential benefits, the single-pilot paradigm is still debated and challenged since the same or even a higher level of safety must be proved with respect to normal dual-crew operations. Simultaneously, the economic viewpoint can also be vital as the adoption of SPOs will heavily rely on weighing the costs against the benefits of necessary investments in developing or adjusting new technologies. Operational costs are widely acknowledged as the largest portion of the price per single aircraft [5]. When considering a life cycle of more than a decade, therefore, reducing the number of crew members in the cockpit can have an immediate effect on this expense. What the interested companies should focus on, then, is refining their estimation of cost savings while simultaneously evaluating and mitigating new risks that may arise.

To date, demonstrating the technical, operative, and commercial feasibility of SPO, remains an ongoing topic and point of contention. Some manufacturers, anyway, already revealed the interest and visions for single-pilot airliners [6], as the case of the Brazilian Embraer. Within the single-pilot cockpit, evaluating the perceived workload is crucial to control the pilot level of engagement to eventually let the automation do some tasks when s/he is out-of-the-loop. Assessing and mitigating the potential risks associated with fatigue or cognitive impairment, also, is essential to ensure safety. Pilot incapacitation, for example, can pose serious risks to flight safety and need to be effectively addressed and prevented. As automation gradually takes on some of the co-pilot's responsibilities, research on SPOs must also address the Human Factors aspect. This will be a significant challenge for establishing effective collaboration with the envisioned assistance systems. An excessive increase in the machines' automated features, on the other hand, can result in humans perceiving additional cognitive loads, thereby affecting various cognitive functions such as long-term, working, and prospective memory. Currently, substantial efforts are underway to evaluate the potential of new flight assisting systems. These cognitive assistants are currently being investigated at academic and industrial level for their ability to reduce the flight deck complexity and support the pilot's decision-making. This kind of system would aim to dynamically reconfigure the flight deck based on real-time assessments and predictions of the pilot's cognitive state. On one hand, the classical approach to these assistants stem from the military domain as it involves tracking whether the pilot is deviating or not with respect to a predetermined task workflow [7]. On the other hand, an increasing amount of studies is emerging nowadays aiming to examine the way to correlate the pilot's mental state to specific physiological signals. A comprehensive review on the topic of Pilot Monitoring can be found in the Luzzani et al.'s contribution [8]. Despite the different assumptions these approaches are built on, the ultimate and shared goal will be the same, since the need of a single-pilot oriented cockpit will be to take in charge all or some of the tasks when the pilot's stress level is high or an incapacitation occurs.

2 Motivation of Work

Given the complexity of the topic, the primary areas of interest for exploring the single-pilot cockpit concept are frequently fragmented at a subsystem level within the literature. Various topics inherent to the research on the single-pilot paradigm are already known to serve indeed different purposes. To our knowledge, only a few systematic literature reviews can be found in the open literature, such as the works by Schmid et al. [9] and Wang et al. [10]. Both these studies employed rigorous inclusion criteria, focusing solely on peer-reviewed studies related to commercial aviation while excluding contributions from General Aviation and military domains. In particular, the paper by Schmid et al. [9] employed a split in the literature that follows up the five research issues identified for SPOs during the 2012 NASA Interchange Meeting [11]. These include operational issues, automation issues, pilot incapacitation, social/communication issues, and certification issues. On the other hand, the review by Wang et al. [10] takes a different approach, focusing on the progress of Human-Centered Design (HCD) research over the past two decades as a crucial element for the single-pilot implementation. Both these works, however, briefly mention the importance of cognitive assistants for the development of SPOs. The idea of assisting agents for pilots trace back to a consolidated military background, as said. This need was particularly enforced by the fact that the military mission scenarios normally require subsystems which are capable of improving in-flight efficiency (e.g., through information management, audio interfaces, automatic operations). Cognitive assistants are actually an important milestone in advancing the concept of Human-AI Teaming (HAT) as explained in the associated guidelines established by the European Aviation Safety Agency (EASA) for commercial flights [12, 13] (e.g., providing optimized diversion options or suggesting optimal route selections).

The present paper aims to review the current state of the art regarding the SPO concept, proposing the selection of sub-topics which are directly or indirectly related to it. A scoping literature review has been, therefore, conducted to serve as a first step to map the inherent peer-reviewed contents including journal papers, conference papers, magazines and relevant websites. Our contribution takes a more expansive perspective on the subject than a specific review, encompassing the wide range of proposals that have been put forth over time, up to and including virtual pilot (cognitive) assistants.

Within this survey, three key and very general thematic domains are identified. The initial two sections, labeled as operations and automation as in Ref. [9], delve into reviewing the different strategies to fit the current infrastructures to SPOs. Also, these section summarize the challenges associated with the expected increase in on-board automation. Unlike other general reviews that barely introduce them, the third section deals with virtual pilot assistants. A growing interest on the topic is indeed taking place. No exclusion criteria were applied to avoid research coming from the military sectors. The structure design of this manuscript can lead the reader through a progression in the literature that culminates in the discussion on the role of Artificial Intelligence in SPOs.

Mainly, the procedure has involved sourcing information from the Google Scholar and IEEE Xplore databases, with focus on prompts such as “aviation single-pilot operations” and “reduced crew operations”. Irrelevant content was initially filtered out based on titles and abstracts in order to ensure a focus just on aviation-related topics. To manage the abundance of available sources, our investigation also prioritized the most cited cross-references within key sources such as the existing literature reviews or prominent content in Google Scholar. As the survey delved deeper into the specific thematic areas explained above, then, the search criteria were adapted accordingly. Specifically, a dedicated search has been conducted on the expression “digital flight assistant”, since the range of applicability of this concept can also go beyond single-pilot flights. To that extent, we undertook further research sessions exploring challenges and open topics associated with the digital assistant implementation. Other queries were, therefore, entered into the search engines with the prompts “pilot health monitoring”, “subjective workload assessment tools”, “artificial intelligence for single pilot operations”, and “pilot incapacitation”. Overall, the review ended up with 128 references. Despite the approach is less rigid compared to a systematic literature review, we believe that the structure of this manuscript can serve as a groundwork for a more comprehensive and careful study in the future. Our examination of selected sources revealed a notable increase in the recent literature, as illustrated in Fig. 1.

This survey confirms that the challenges associated with future single-pilot operations implementation in commercial aviation will mostly regard the interaction between humans and machine. Although technology is advancing rapidly on many fronts (e.g., voice interaction and workload estimation), what will matter in making single-pilot flights a reality will be defining operational requirements and ways to integrate on-board automation into the role of an additional teammate (not substituting rather relieving the human duties). On this side, shared awareness among

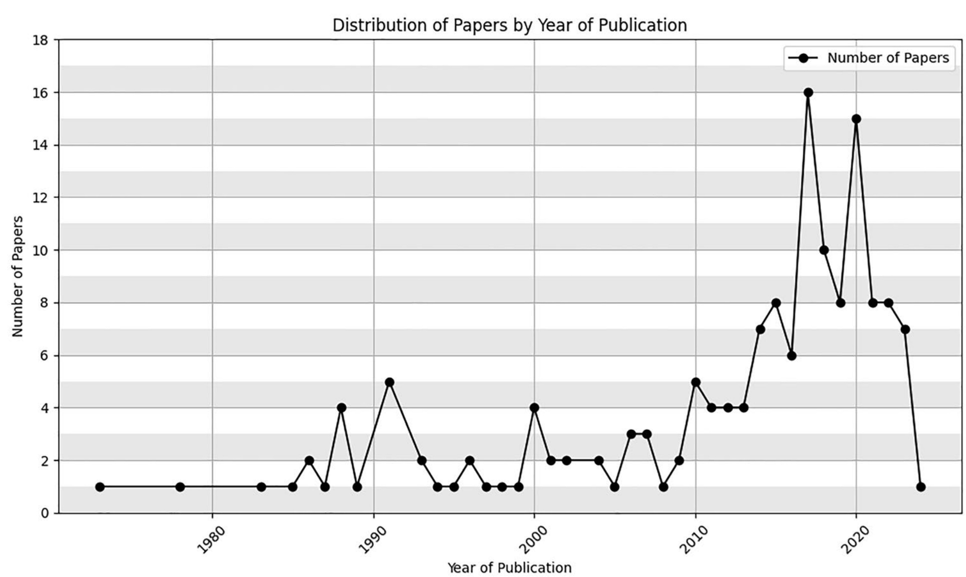


Fig. 1 Distribution of the selected papers by year of publication

on-board agents should be promoted through operator-directed interfaces so that pilots avoid the risk of increased training efforts and find the right balance between over- and under-dependence on on-board subsystems.

3 Operations

Up to now, the concept of single-pilot operations has mostly been limited to General Aviation (GA) and military domains. Just recently, SPOs have been extending into the Very Light Jets (VLJs) market, too [14]. Over the last few decades, several research campaigns with simulators have been dedicated to analyze the impact of SPOs on these jets. Some examples [15, 16] show how researchers examined strategies for reallocating workload and automation roles. This surge of interest in VLJs, then, soon triggered the general opinion about SPOs. In their manuscript, Matessa et al. [17] outlined the principal concepts of operations for extending the Single-Pilot paradigm into the commercial aviation sector. The authors indicate that adding supporting ground units should be the pivotal aspect in addressing the challenges posed by the loss of Situational Awareness (SA) during non-nominal flight conditions. With this modification, the aircraft will be part of a wider system that accounts basically for a ground-based operator acting as a second remote co-pilot. With the passing from amateur light jets to the complex world of commercial aviation, anyway, the remote piloting solution runs out into major issues concerning safety and security. An important cornerstone for the Human Factor research on the topic was in fact to demonstrate that ground assistance for SPOs should be heavily based on similar teamwork dynamics to those existing in a dual crew.

Aircraft are an intricate and complex system. Cognition is distributed among multiple agents, and this resulting *system-of-systems* is normally designed to perfectly operate when all the agents perform their role and are aware of the personal and mutual limitations. With the born concept of Human-Autonomy Teaming [18], in fact, researchers recognized that automation must be an essential part of such a social network. Lachter et al. [19] involved professional pilots in performing non-nominal flight scenarios to examine the possible challenges caused by the physical separation of the crew. When not sharing the same space, pilots stand no significant variation on their perceived workload; nevertheless, some lack of non-verbal communication might happen with possible misunderstandings on their own duties. Mosier et al. [20] conducted a study involving 20 interviews with pilots, aviation experts, and dispatchers from various organizations. Participants were asked to provide subjective feedback about flying alone on board and with increased assistance from the ground. A group of participants highlighted the necessity for frequent and more precise communication between air and ground to compensate for the loss of visual information and non-verbal cues. Moreover, several interviewees emphasized the importance of training, expressing concerns about the feasibility of the current Crew Resource Management (CRM) procedures. Consequently, the regulatory authorities are being contemplating an innovative approach called Single-Pilot Resource Management (SRM) [21]. Although the research on SA [22] has traditionally considered it as an interaction-based phenomenon, SRM will aim to harness the pilot's ability to maintain SA both at individual and teaming level. Some concern was, therefore, posed (see Sorensen et al. [23]) on simply adapting some of the score-based techniques for individual SA assessment to the case of a completely new hierarchical team structure. Clearly, a training issue also arises for remote operators on the ground [1, 9]. Other aspects were underlined for training the future pilots of commercial aviation, such as the need for a better handling of fatigue in long-haul missions, or facing skill degradation connected to the more advanced systems on board. Up to date, training issues for SPOs have been addressed just with early theoretical reviews. Costs analyses are urgent in this sense to assess whether the overall concept of single-crews would still be worth from the economic perspective. Schmid and Stanton [9] proposed an introductory loop of training for SPOs, which should be built on a gradual transition. Job rotations between air and ground operators can be necessary in the process of forming new Captains. Also, the first operations on these new flight decks are recommended to be assisted from trainers before their full-spread.

3.1 Ground Assistance Operative Scenarios

Unlike what happened with flight engineers in the last century, this time, replacing the role of the co-pilot goes beyond simply transferring tasks or responsibilities to another agent. A necessary step for enabling SPOs will be in fact to perfectly discriminate the roles of the agents in their different environments. Based on the guidelines discussed in the 2012 NASA Single-Pilot Operations Technical Interchange Meeting [11], a crucial component of the single-pilot operations implementation process will be to figure out the correct configuration for the additional staff on the ground. Ground officers would in fact be as much involved as the pilots during the most critical flight phases. Also, the ground staff responsibilities will encompass perception, attention, memory, situation awareness, and decision-making skills [24]. Vu et al. [25] provide a summary of the recent proposals. What emerges in the debate is the way to deal with the manifestation of a non-nominal or emergency scenario. Pilots in fact generally prefer a prompt ground-based assistant with First-Officer duties in these cases, that should come in place only when requested explicitly [1, 26]. The solution would be in definitive terms to have one pilot on board, with a ground-based team member replacing the second pilot. Such a change can be seen in the schematic sketch in Fig. 2. Specifically, the reader can focus on the extra element that arises in comparison of the current operations. This is the real-time engineering support to the flight, provided through the cockpit mirroring on the ground (see Fig. 2).

Beyond the normal air traffic control infrastructure, therefore, it has been claimed that a ground-based second pilot support station will be necessary for SPOs. To define the roles and responsibilities of such an extra additional level of

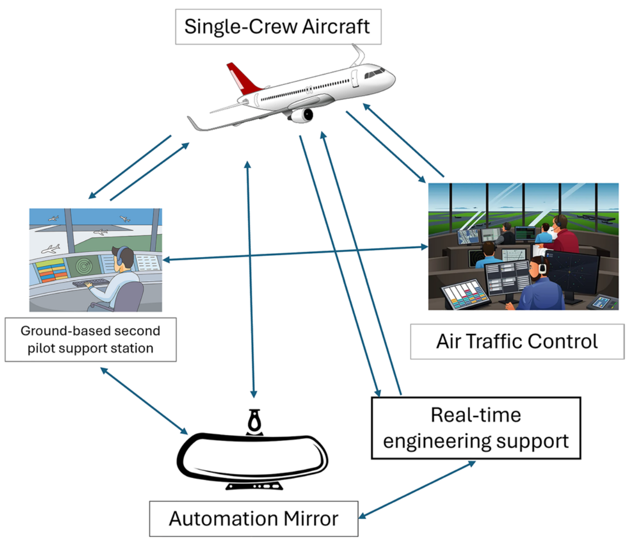
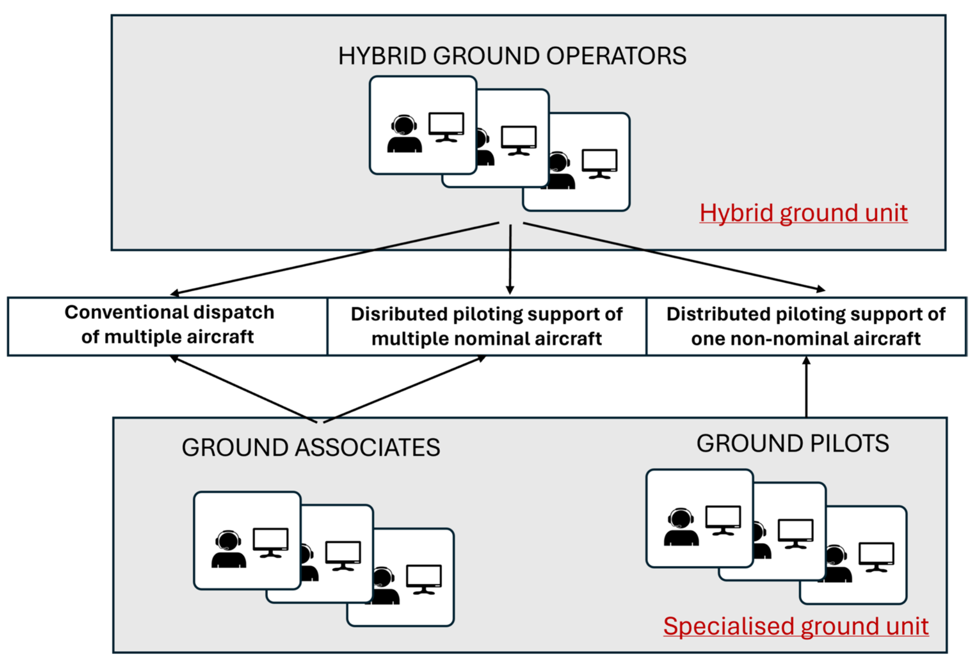


Fig. 2 Sketch of the possible infrastructure foreseen for enhancing single-pilot flights, with one pilot on-board and a ground-based team. One more assisting station should be added apart of current ATCOs. Adapted from Stanton et al. [27]

assistance, however, there have been significant discussions in recent years. Operators on the ground, in fact, can face the challenge of managing excessive workload as they cannot always be fully aware of the situation on all the aircraft they are responsible for. To overcome this issue, two opposed philosophies were defined, which are encapsulated in the concept of hybrid and specialized operators, respectively (see Fig. 3).

- **Hybrid Ground Operators**: Ground officers should perform an hybrid role, keeping the exercise of dispatching functionalities and offering at the same time distributed and dedicated piloting support. One operator, in other terms, could be enrolled at the same time in the normal assisting duties, plus the piloting support both for nominal aircraft and for those that are issuing problems. Opinions from debriefing sessions with pilots serving as ground operators reveal the potential risk of losing awareness of other flights when engaged in first-officer duties. While the hybrid approach can be the one to provide economic advantages, all the roles that the operator will have to act might create overloads [26, 28]. The first image at the left in Fig. 4 may be representative of this condition, where the single individual should address multiple roles for different aircraft with different needs.
- **Specialized Operators**: On the other hand, this other concept considers to split up the roles on the ground and allocate one group of operators for each functionality. Specifically, one group will always act as a backup support for those aircraft that are experiencing troubles and are in non-nominal conditions. With this concept, each time an aircraft is in danger, an operator from a special-

Fig. 3 Hybrid ground unit vs specialized ground unit. Adapted from Bilimoria et al. [1]



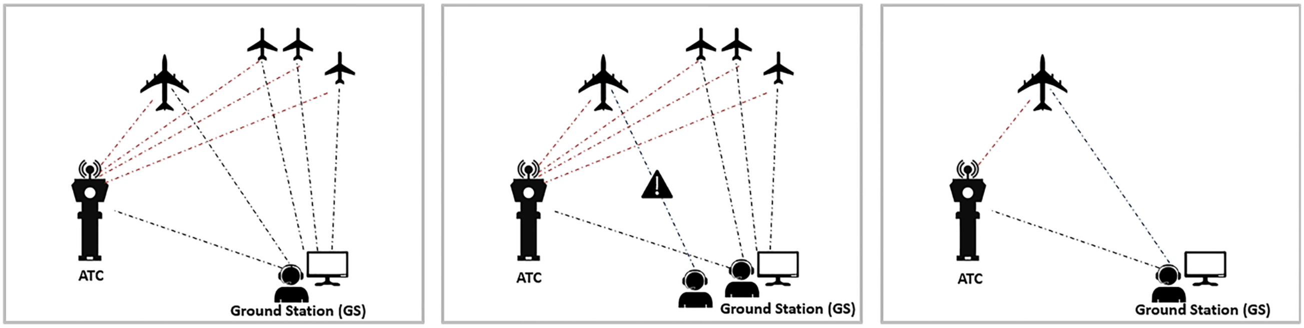


Fig. 4 Comparison involving the concept of hybrid and specialized assistance. Adapted from [30]

ized group is assigned to that flight. The middle image in Fig. 4 shows this scenario. Testing such a dedicated assistance paradigm for the entire flight can be an expensive choice. A worth solution could be to implement it just for critical time windows. Some proposals in this sense have been made, as for the Harbour Pilot (HP) described by Koltz et al. [29]. The HP is the ground operator who would assist single-pilot aircraft during departures and arrivals in specific and complex flight areas, such as airports and their surroundings (see the image at the right in Fig. 4).

As of the present date, none of the previously mentioned proposals can be unequivocally labeled as the best choice for SPOs. Asokan [31] conducted a comprehensive trade-off analysis considering costs and safety implications of various high-level architectures. According to the author, the benefits and costs associated with transitioning to SPOs will vary depending on the type of aircraft. Regional carriers, for instance, stand to gain significantly from the reduction to a single-pilot crew. The estimates [32] suggest that up to 35% of the total operating costs for flights covering less than 200 nautical miles and carrying fewer than 50 passengers are attributable to the expenses associated with the crew.

Regarding the management of pilot incapacitation episodes, the conceptual framework proposed within the European project SAFELAND [30] carries out another approach for enabling SPOs, with a focus on the air traffic management (ATM) perspective. According to this work, each major phase of the flight (departure, cruise, and approach) should involve a different ground station. Doing so can in fact prove an increase in safety. The authors consider, therefore, the possibility of having an high-fidelity remote pilot station to employ when an intervention is required during non-nominal situations. Operating with the remote piloting, thus, can give sufficient time to the operators to familiarize with the flight's progress before assuming the full control during an handover process. An illustration of an example protocol for managing pilot incapacitation has been drawn from [30] and presented in Table 1. Workload can be spread across the operators, regardless of the economic effort associated with hiring more personnel. An opposite opinion was formulated by Harris [33], who argued that, to minimize costs, national and international aviation providers should try to leverage on the existing infrastructure features rather than embarking on a complete rebuilding.

Table 1 Phases identified for handling a pilot incapacitation episode during the cruise phase. Adapted from the SAFELAND concept [30]

	Description
Step 1	On-board system detects pilot incapacitation
Step 2	Automation keeps aircraft stable and follows last clearance. Cruise ground station operator (GSO) confirms and declares incapacitation
Step 3	Cruise GSO takes over control, squawks emergency code. ATC clears airspace
Step 4	Handover to stand-by GSO
Step 5	Automation provides list of suitable airports
Step 6	Stand-by GSO decides diversion airport
Step 7	GSO requests clearance for emergency landing
Step 8	Emergency landing based on autopilot data

3.2 Function Allocation

As previously mentioned, the primary focus is on the modifications required for flight procedures to maintain an acceptable level of safety while accommodating single-pilot operations. An early high level function analysis was given by Boy [34], who underlined the necessity of keep going in producing more detailed or specific function and task allocation models. Apart from the interviews-based surveys, indeed, most of the recent papers on SPOs involved simulator-based test campaigns aimed at confirming the theoretical models with the support of well-known tools. Lots of tools from the field of human-centered design (HCD) came, therefore, into practice as valuable approaches to constrain the different cognitive functions of the agent, either for dual and for single-crew applications. Some examples of task decomposition for approach-and-landing scenarios have been achieved using spreadsheets [15] or specialized platforms [35]. More than 100 models are listed in Diaper and Stanton's handbook in Ref. [36]. Generally, the task descriptions follow a structured hierarchical approach [37] in order to specify all the potential logical constraints and the relationships between the tasks. A more recent scheme called operational event sequence diagrams (OESD) was presented by Harris in Ref. [38] and aimed to emphasize the timing and sequencing of the activities. Validation processes for these techniques have primarily involved intensive briefing sessions with subject matter experts, supported by data acquisition sessions with pilots. Other analyses in the literature such as Refs. [39–41] undertake what has now become a standard analytical framework under the name of Cognitive Work Analysis (CWA). A toolkit for this was designed by Read et al. [42] consisting of further techniques that progressively transform Human Factor indications into design choices. Each technique [34, 38, 43, 44] 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).

Recent contributions introduced tools to evaluate the level of interaction between the agents. Stanton et al. [45] carried out a function allocation using the CWA framework in combination with the metrics of a social network analysis [46] (SNA). Such analyses are based on the intuitive notion that the pattern of social ties in which the operators are embedded might have decisive consequences for them. With SNAs, agents will become nodes of an articulated graph, with a precise math-inspired metrics to constrain complicated design choices. Apart from the human agents in the loop, the task reallocation will also involve the automated systems on-board. To this extent, the work of Piera et al. [47] can be cited as this provides a more recent overview in the way of modeling the dynamics involving these two kind of agents (human and non-human). A socio-technical simulation model was introduced in this contribution, with a new modeling methodology to formalize the hidden dynamics that involves technological supporting tools and cognitive processes.

4 Automation Enhancement

According to the literature, another important line of research for enabling single-pilot operations is about introducing advanced technologies on-board, aiming, therefore, to replace the co-pilot functions. Several authors claim in fact that enhancing the on-board automation characteristics might be a valuable solution to prevent the drastic modifications of the air transportation infrastructures that are described in the previous Section. As automation levels advance [48], the role of humans in effectively navigating system complexity becomes even more essential. Consequently, the consequences of errors related to the Human Factor perspective can be more severe. While numerous tasks can be automated, the crucial question for SPOs arises as to the extent to which this automation should be allowed. Automated systems should be in fact introduced without squeezing the flight crew into purely monitoring and managing roles. Standing by the side of the pilot through the design of more intuitive interfaces was already conceived within some early NASA references [49, 50] that dealt with so-called intelligent cockpit assistants. Several operational and social challenges should be solved, anyway, before the implementation of such concepts in the airline industry. Malik et al. [51] analyzed different operational scenarios, considering the progressive reduction of the crew until reaching a point with no pilots on board. The authors suggest that single-pilot operations might also serve as a transitional phase toward a fully automated cockpit.

Just relying on improving automation, anyway, might not be enough because of the difficulty in obtaining airworthiness certification. According to the currently proposed design scenarios [25], some level of redundancy on the ground will still be necessary to ensure that single-pilot operations are as safe as or even safer than current operations. Automated systems can indeed play a synergistic role with ground operators, serving as primary detectors for potential incapacitation episodes in the cockpit. Also, most of the monitoring tasks traditionally assigned to the co-pilot could be delegated to automation, allowing pilots to remain sufficiently responsive. Collecting pilots' opinions with structured interviews has been crucial in the last decades to indicate solution paths for this new design philosophy of the flight deck. Surveys generally supported the idea of having reliable systems producing predictable results [52]. As automation becomes more integrated into shared decision-making processes, interactions between the agents on board should be managed. Several studies focused on enabling more intuitive interfaces, visual or auditory cues to facilitate the pilot during standard operations [53, 54]. All the risks connected to phenomena such as automation bias [55] or complacency must be avoided.

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 and further. In addition, a historical overview of proposed taxonomies for categorizing levels of automation is provided. A summary of the main findings is given in Table 2.

4.1 Adaptive Automation and Levels of Automation (LoA)

Automation is generally defined as the act in which a machine agent performs a function that was previously in charge of an human being [61]. The Oxford English Dictionary defines it, by extension, as "the use of electronic or mechanical devices to replace human labor". Some early attempts to determine whether humans or machines were better suited for specific functions can be traced back to early 50s in the last century. An important and much referenced research on this front traces back to the work of Fitts [62], that supported the idea for which humans should focus more on inductive and judicious reasoning while leaving mechanical and precise activities to machines. As time went on, the line between the two became increasingly blurred. With the transition to single-pilot operations, the new Human-Centered Design paradigm should be considered. According to the ISO definition, HCD "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 systems gained significant attention in aviation when the introduction of glass-cockpits led to replacing the role of the flight engineer. Warnings soon emerged, however, as some systems ended up with reducing pilots' workload in situations when it was already low and increasing it when it was high, contrary to the intended outcomes.

As already mentioned, enabling single-pilot operations will still require to date an human supervision. Early discussions on this matter are documented in the work of Chambers et al. [63] from the NASA Ames Research Center. The authors, here, recognized that pilot errors are systematic. Despite the motivations for increasing levels of automation inside the cockpit were already envisaged at that time, authors underlined their strong and pessimistic stance regarding the anticipated reduction in human errors with automation. Although the increase of automation, in fact, the locus of errors can still shift in kind and time. Brown et al. [53] conducted a 3 decades review, investigating the lessons learned about the impact of automation on Human Factor in aviation. A valuable approach for this would also be the reconstruction of accidents, as these often provide scenarios that reveal both the advancements and potential challenges associated with automation. Within the manuscript, Brown analyzed a recent accident with the aim of identifying the potential contributing factors with a practical example.

Complacency is described as the failure to be vigilant in supervising automation prior to the automation failure. Wickens et al. [55] report automation complacency as a possible cause of the attentional tunneling phenomenon. On the other hand, the out-of-the-loop syndrome occurs when users fail to continuously recognize what the automation is doing or not, often by excessively focusing on instrumentation and neglecting their physical surroundings. Most automation systems also suffer from brittleness, as described in the work of Christoffersen et al. [60]. In other words, a system's performance may be good for the range of situations for which it was designed, but it requires human intervention to handle situations outside those environments. Other issues deal with cultural considerations, especially concerning the way authority gradient in the cockpit modify when considering the automation as an additional member of the crew. According to the survey by Parasuraman [61], operators should try to avoid what are recognized as "misuse" and "disuse" scenarios, as well as the complete abuse of the automated systems' capabilities. A possible cognitive overhead in managing an automated subsystem could, in fact, even outweigh its potential benefits, so much to make it less attractive.

As often acknowledged by industry insiders, technology challenges are not the primary obstacles for the practical implementation of single-pilot operations to date. Rather than simply automating a function, current designers should focus on determining the extent to which to do so, understanding when and why an aid should be used and the conditions under which it might be left unused. Some research around the topic of managing different automation control modes was already addressed by Kirlik [56], who analyzed some possible optimal policies for using the autopilot in both single and dual-crew conditions. Within the manuscript, Kirlik demonstrates 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. This 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

Table 2 Summarizing the main papers involving cooperation between operators and automation agents within and beyond the aviation sector

References	Problem/purpose	Main conclusion
Bainbridge [48]	The introduction of additional layers of automation to human-conducted activities can lead to unexpected outcomes	Methods to alleviate these problems within the classical approach of leaving abnormal conditions to the operator are discussed
Kirlik et al. [56]	Operators can adopt various strategies to manage their interaction with aiding systems. The successful design of task-offload aid systems requires knowledge of task-contextual factors influencing operators	A model is presented and tested with a laboratory test, showing how such strategies can be predicted as a function of task context and aid-design properties
Sheridan et al. [57]	Classify the modalities of automation interaction with humans	A ten-point scale is proposed to classify different Levels of Automation (LoA), discussing the relative roles of humans and non-human agents
Parasuraman et al. [58]	Classify the modalities of automation interaction with humans	A two-variable taxonomy is proposed and applied to different functions of the system, helping to decide which functions should be automated
Save et al. [59]	Classify the modalities of automation interaction with humans	A Level of Automation taxonomy is proposed to support and derive automation design rules in ATM scenarios
Brown et al. [53]	Examine the main issues arising from the introduction of automation from a human factors perspective	Some aviation accidents are examined to determine the factors contributing to automation-induced human errors, introducing new approaches to deal with them
Wickens et al. [55]	Compare the performance decrements caused by different types of unexpected automation errors through humans-involving tests	Automation bias is identified as a more problematic form of error than complacency, suggesting strategies to mitigate it
Yvette et al. [52]	Survey airline pilots to collect opinions on possible high-level automation problems and ideal cockpit design directions	Respondents to this survey recognized the need to ease the mental workload imposed by further automation, suggesting a shift to shared systems
Mosier et al. [54]	Collect pilots' judgments on how variations in automation interface characteristics and tasks impact their performance and cognition	Even small changes in automation modes can have a broader effect on pilots, affecting their judgments about crew workload
Christoffersen et al. [60]	Propose norms for realizing a joint system between humans and machines where machines behave as team players	Design processes should consider observability and directability to enable users to see and intervene in machine activities as needed

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 in the literature [43, 64] 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 [57], for example, proposed a 10-point scale based on automation applied to decision-making moments within the human information processing.

A subsequent analysis by Parasuraman [58] outlined a two-variable taxonomy for the Air Traffic Management activities having the level of automation on one variable and the processing stages on the other. According to this 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 presented by Save [59], whose proposal was derived from the same problem coming from a different domain (automotive). According to [59], indeed, a right taxonomy design should highlight that the level of automation depends on the function of the human–machine interface that is being supported. This means that one automated system can support multiple goals at a time, for which the practical amount of automated features can be slightly different (the functions are information acquisition, information analysis, decision-making and action implementation). Unlike the work of Parasuraman in Ref. [58], which leads to the same conclusion, the author in Ref. [59] provided a more context-aware description of each processing stage function in the air traffic control scenario. An adaptation of the full-model is summarily shown in Fig. 5.

4.2 Evolution of the Flight Deck

What is now termed "glass cockpit" was introduced by Airbus with the A320 family in the mid-1980 s, followed by the 747 and MD-11 in the early 1990s. Glass cockpits replaced traditional dials and gauges with computerized displays, providing flight crews with precise and quick access to data. As safety requirements increased over time, anyway, the current design of the flight deck is too complex for being shifted to SPOs. Modern pilots often need to manage information from various sources simultaneously. Chandler et al. [66] suggest, in fact, that pilots may perform better with single integrated sources of information, emphasizing the need for streamlined and accessible interfaces. The ideal cockpit for single-pilot operations should, in fact, just shed light on the information which is relevant to the context. Within their manuscript, Faulhaber et al. [67] proved that the scanning patterns of the single pilot will necessarily change with the absence of the First Officer, becoming more dispersed over a larger number of secondary instruments. One of the necessary steps that are envisaged for the transition to single-pilot operations will be, therefore, to reconsider the current design of cockpits in such a way to accommodate new cognitive interfaces between automation and humans. Automation should be designed to maintain continuous

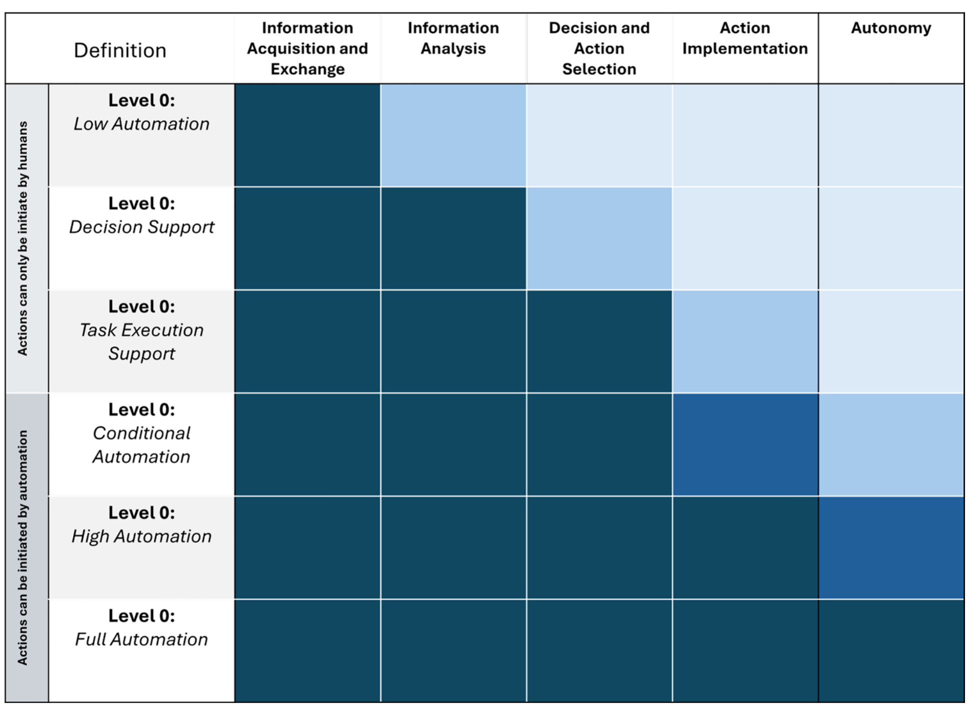


Fig. 5 Color scale representation of the taxonomy of automation levels provided by Save et al. [59], ranging from 0 "no automation" to level 5 "full automation." Each level is further decomposed into the amount of autonomy expected for the individual processing step (blue scale). Adapted from [59] and [65]

communication with the pilot, possibly using a human-friendly vocabulary that eliminates the need for the pilot to translate from machine status to mission objectives. Schutte et al. [68], for example, introduced the concept of the Naturalistic Flight Deck (NFD), with the aim of improving on-board interactions with automation. At any time, the machine must be able to state its intentions in terms that are understandable to the pilot and relevant to the mission. With their manuscript, Thomas et al. [69] provide insights into the state-of-the-art and emerging control devices for managing the interaction with automation, either for the ground and the airborne personnel. A notable focus was given to head-mounted displays, which have the advantage of enabling the concurrent scanning of instruments data and the outside scene. Some concern, however, was reported for cognitive issues associated with their use, such as attentional tunneling or cognitive capture [70]. Gesture-based control remains instead a less-regarded area of research. Some ideas have been proposed to implement interactions with 3D virtual panels simply using hands or fingers positioning. 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 [71]. An important contribution to these topics was firstly given by Furness' 1986 paper [72] about the design of the so-called Super Cockpit for military applications. Since his experience with the sphere of augmented reality, Furness suggested using a head-mounted system to project information into an immersive 3-D virtual space, enabling pilots to view and hear real-time data. This approach was designed to enhance the pilot's ability to comprehend and manage information effectively. The system also included a tracking system, voice-activated controls, and sensors, allowing pilots to control the aircraft through gestures, utterances, or eye movements. Moreover, the Super Cockpit should have included an interface with a special-purpose processor called a "pilot intent inference engine", anticipating the role of the modern Virtual Pilot Assistant (VPA) architectures. This system would have to screen, filter, and control the flow of information to the pilot based on the interpretation of the pilot's information needs during various mission phases.

Coming to the present time, research has been focusing on smart adaptive subsystems that can be activated based on a quantified measurement of the operator's cognitive workload. Unconventional interaction methods are being explored to create more intuitive interfaces, such as eye and gaze-tracking techniques [73, 74], gesture or voice controls, or haptic-feedback control devices. A summary of the main findings regarding this paragraph is given in Table 3.

5 Digital Flight Assistants

The topic of single-pilot operations is often associated with the implementation of a so-called Digital Flight Assistant (DFA). Such a concept was already envisaged in the last century. Chambers et al. [63] discussed indeed a scenario where automation could be significantly more autonomous, and the pilot functioned as a passive monitor. Current research is exploring the integration of these concepts both in the cockpit and in ATC stations on the ground. A few past projects can be mentioned in this regard, such as ACROSS [75] (Advanced Cockpit for Reduction and Workload) or ALIAS (Aircrew Labour In-Cockpit Automation System). With the more recent SESAR 3 Joint Undertaking project JARVIS (Just A Rather Very Intelligent System) researchers' aim is to generate a larger framework with three AI-based solutions, involving airport specific assistance, too. A concept image of JARVIS is shown in Fig. 6. Concerning airborne operations, these virtual flight assistants will deal with the scenario of a single pilot on board, with automation replacing the second pilot and providing support to compensate for this loss of redundancy.

A digital flight assistant can basically be seen as a knowledge-based system that reduces workload in the cockpit through increased system autonomy and closer collaboration with the ground components. Of the many goals, the most crucial is that these systems must be ready to manage aircraft controls in the event of pilot incapacitation, either through direct intervention or by facilitating the remote intervention of a ground-based operator. Some of the key points regarding the advantages and disadvantages of a DFA are listed below:

- Although generally considered as good troubleshooters, all pilots are prone to boredom, complacency and over reliance with respect to automated systems. The virtual pilot assistant can provide real-time updates, alerts, and recommendations to help them maintaining a high level of Situational Awareness. One important requirement that the assistant has to meet is, in fact, the presence of adaptive interfaces aiming to reduce the flight deck complexity.
- Since the on-board automation is expected to increase either numerically and in its complexity, each system should also assume the implicit role of non-verbal communication which is typically observed between human counterparts. Considering a virtual assistant, then, voice recognition capabilities are an important requirement to make it responsive to any request for help from the pilot.
- Confusion over an automation system's current mode of operation can lead to misinterpretation or inappropriate

Table 3 Approaches to new flight deck tools and philosophies

References	Problem/purpose	Main conclusion
Chandler et al. [66]	Within the description of cognitive load theory (CLT), authors argue that split-source information can generate a negative load for who has to perform it. Practitioners must be directed to activities that are not only preliminary to learning	Six experiments were conducted to support the general idea that in areas where mental integration is essential in order to make sense of two or more sources of information, conventional instruction modalities should be enhanced
Faulhaber et al. [67]	Using a fixed-base A320 simulator to examine whether the experienced pilots' scanning behavior can be affected by the absence of a Pilot Monitoring	Participants spent significantly more time scanning secondary instruments at the expense of primary instruments when flying alone
Schutte et al. [68]	The paper introduces the holistic design of the Naturalistic Flight Deck (NFD) as a mean to increase the safety, reliability, and performance of single-pilot operations	Complementary automation is given as a design principle. The human should be called upon to make just high-level changes, while the automation handles the inner loop control and monitoring
Thomas et al. [69]	Reviewing and find the direction of research in pilot human-computer interaction (HCI) for both civilian and military aircraft, with regards to Cursor Control Devices (CCD)	Some different bio-centric CCDs were investigated during a point and selection task experiment, such as eye, head and hand trackers
Fadden et al. [70]	Giving the result of a meta-analysis conducted on the cost-benefit comparison between head-up and head-down displays in aviation	The paper argues that HUDs have been shown to improve tracking and detection in general. Some exceptions include cruise and approach phases or situations where unexpected events can occur
Bollmann et al. [71]	Describing the language processing part of an Approach Briefing Assistant based on Artificial Intelligence	The application is promising even in the presence of noisy environments. This early characterization is based on a dual-crew scenario. Steps towards a possible certification are outlined
Calhoun et al. [73]	The purpose is to test eye-controlled switches inside a cockpit simulator	The analysis suggests that eye control is a feasible alternative when hands-off control cannot be performed
Merchant et al. [74]	Analyze the eye-tracking techniques capabilities to serve as alternative control technologies in human–machine interfaces	The steps of the process to build a simulator with two alternative eye-tracking method have been described in this paper

Fig. 6 JARVIS is a SESAR 3 Joint Undertaking project, co-funded by European Union's Horizon Europe and including 16 partners. The main aim of the project is to implement and validate three digital assistants to team with their human counterpart in aircraft, airport and air traffic control stations. Credits to: https://research.dblue.it/jarvis/

actions. The central role of the DFA concept must be that of facilitating the shared knowledge between the human and automated agents.

- The enabling approach would be to characterize the interaction with the assistant so that it can behave as an additional team player in the crew. The assistant would have to be based on an interface with a two-way communication paradigm that is transparent and strictly directed to the operator.
- Similar to aircraft computers, pilots continuously monitor aircraft states and environmental information. At the same time, the virtual assistant should apply the same approach even to a broader level. The aim would be in fact to track the flight status and control the execution of the main duties of the pilot at each time.

One approach to make these tenets applicable for Human-Automation Teaming can be to consider an intermediate buffer that stands between the pilot and the automation itself. This possibility has been foreseen in the conceptual work of Shively et al. [18]. Such an agent would be able to intercede between the pilot and the automation. This would translate the very and raw calculation of automation and retrieving those to the pilot in the most flexible and adaptive way. As reported in the conclusion of the Shively's research, in other words, the automation returns possible courses of action, and information about the rationale for their selection, and confidence in their success. These results are then filtered when passing to the HAT agent based on the current context to avoid having too much information overwhelming the pilot.

Gosper et al. [76] provided a survey about how professional pilots can perceive the role of a digital assistant. According to the surveyed pilots, despite the potential of giving a challenging entertainment during the flight, the conversational aspect of a digital assistant might be interfering with the already existing work practices. This will inevitably lead to formulate new operational procedure with a dedicated training. Some participants were also skeptical about the role of the audio communication. The problem could be in fact the presence of high noise in the cabin that can interfere with the communications. Although into an embryonic state for the civil counterpart, research considers that virtual assistants can simplify the way humans access to the aircraft's automated systems, centralize decision-making and increase the Situational Awareness of the pilot. A complete description of the architecture for a certifiable virtual assistant was initially proposed by Lim et al. in 2017 [77], still remaining the same in the next years. Some other articles were published later on with more practical applications of assistance to SPOs. Cover et al. [78], for example, evaluated a tablet-based rerouting and divert software suite with the help of professional pilots in the cockpit of a high-fidelity simulator. Such a system offered assistance through semi-automated electronic checklists, audio/voice cues and commands, thereby demonstrating that these can be valuable and useful tools in the cockpit of a civil aviation aircraft [17, 78].

There are significant contributions in the literature that cover the topic of digital assistants from the military aviation perspective. A comprehensive line of research is in fact still going on at the Bundeswehr University of Munchen (UBM) (Fig. 7), which aim is to develop an associate aiding system [79] in the context of Manned-Unmanned Teaming missions [80] (MUM-T). Since the models employed for evaluating the pilots' perceived workload are still evolving, a general shared rule for the design was to allow the pilot to supervise the cockpit without the automation intervention unless is strictly necessary [79]. Among the related manuscripts, the proposed assistance system [81] was conceived to adapt the extent of support by identifying the current [82] and future task situation and the mental workload of the crew. Such a system operates, therefore, under the assumption that mental workload is a task-dependent construct. A model for describing the tasks must be established beforehand, enabling the assistant to maintain the pilot's workflow within nominal parameters with minimal deviations.

Maiwald et al. [83] introduce the concept of a resource-adapted interaction pattern for an helicopter cooperative assistant. A systematic issue on the topic of a digital assistant in fact to acknowledge that the human operator must invest additional cognitive resources to recognize the assistance given by the automation itself. Assistance should, therefore, be calibrated to consider this as an additive task to perform. An experimental test was carried out, then, to evaluate the enhanced system capability of estimating the spare cognitive resource of the pilot. Mund et al. [84] described a supplementing approach to enhance the performance of the associate system. Collecting significant physiological measures, in particular, might allow the associate system to infer an ameliorated estimation of the workload.

Another crucial consideration pertains to the volume of data that any virtual pilot assistant must handle and exchange with ground stations. Given the diverse spatial distribution of airliners' operators, including single pilots and dispatchers, the quality of transmitted information can significantly vary between dual-crew and single-pilot operations. Consequently, the system faces heightened vulnerabilities, necessitating the establishment of new encryption protocols to safeguard data. At the same time, though, encryption introduces signal transmission delays or latency, which could impede real-time data sharing between aircraft and ground stations. What emerges is that SPOs will necessitate the development of a communication infrastructure with a low latency, high bandwidth, securely encrypted and highly reliable data-link via satellite, which, however, still does not exist.

5.1 Mental Workload

Overall, a Digital Flight Assistant needs to undertake appropriate tasks through the mission to avoid overwhelming the pilot's physical and mental resources. While the concept of mental workload may appear intuitive, defining it has proven to be surprisingly challenging, and a universal agreement has not been reached to date. Most authors, as [85, 86], tend to concur that workload pertains to the level of attentional resources required to meet both objective and subjective

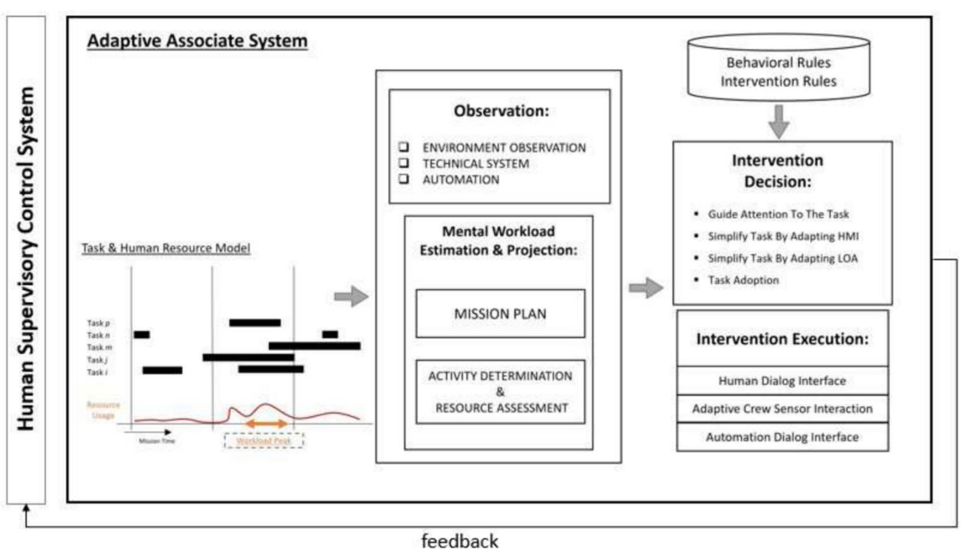


Fig. 7 Functional architecture of the associate system developed at UBM, Germany, adapted from [79]. To trigger the assistance and plan an intervention, the system will both pre-process the mental state of the pilot, predict all the workload peaks and detect any neglected task. The final intervention is provided in the form of reassessing the level of automation (LoA) or adapting the Human–Machine Interface (HMI)

performance criteria, which may be mediated by task demands, external support, and past experience. According to the general consensus, also, both mental overload and underload are considered detrimental to performance, as they are associated with the concepts of active and passive fatigue, respectively [87]. Although the modern aspects of the applications foreseen on SPOs, several discussions on the way to define workload were already started in the past century in the domains of cognitive psychology and pedagogy. Sweller was the pioneer in the field of the Cognitive Load (CL) theory [88], conceptualizing it as the amount of working memory (or short-term memory) resources utilized. Hence, Cognitive Load can be linked to the process of retaining and subsequently processing a set of information within the constraints of human working memory capacity. All such efforts gave origin to the actual consensus about mental workload as an item which, by contrast, mixes the objective and personal spheres. Choosing an appropriate workload metric is, therefore, crucial to ensuring that a digital assistant in the cockpit effectively supports the pilot without imposing additional cognitive demands. Currently, there are several improved methods for providing workload estimations: a) subjective assessments or questionnaire-based feedback strategies such as rating scales or structured interviews (e.g., NASA TLX, Subjective Workload Assessment Technique (SWAT) and others); b) task-based workload models, which basically combine all related task demand together with a measure of their degree of interference and c) psychophysiological-based measurements, based on the addressing correlation of important physiological signals with performance decrements.

5.1.1 Subjective Workload Assessment Tools

Subjective assessments have long been a prevalent method for estimating workload in many sectors apart from aviation. [89] Considerable research efforts have been devoted to finding the best self-report tools to collect data on how individuals perceive their workload while engaged in a task. Common forms include various types of questionnaires and surveys aiming to condense the operators' feedback into a single quantitative score. Subjective techniques do offer advantages such as high subject acceptability, low implementation requirements, and reduced intrusiveness and costs. On the other hand, however, their application is limited as the provided feedback can vary depending on individual perceptions, including stress, fatigue, or a general lack of awareness. Subjective techniques should be as flexible as possible to not interfere with users' primary tasks or cause unintended workload degradation. Casner et al. [90] offers a self-contained review on the pros and cons of the most popular subjective workload assessment techniques. A distinction can be generally made between absolute and comparative measurement techniques. Absolute approaches, in particular, consist of asking the human operator to judge situations in a standardized format and to adopt the evaluation criteria imposed by the experimenter. Some of the most popular examples were derived from military applications. A list is given below:

- **Instantaneous Self-Assessment (ISA)** [91]: This technique involves periodically asking users to report their perception of workload on a scale of 1 to 100. While this method is straightforward and direct, its reliability may be questioned, as it relies on subjective self-assessment.
- **Subjective Workload Assessment Technique (SWAT)** [92]: Participants are tasked with sorting a fixed number of cards containing various descriptions of mental states. The participant's card sort is then correlated to a predefined baseline, resulting in a final workload score ranging from 0 to 100. This method is characterized by its ease of use and low interference with the user.
- **NASA Task Load Index (TLX)** [93]: The NASA TLX consists of a multi-dimensional rating scale with a range from 0 to 100, assessing six key components of task load: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Users compiling a NASA TLX typically have to assign weights to these components, reflecting their perceived importance in relation to the overall workload assessment. Since 80 s, NASA TLX has been adapted and also applied in various fields beyond aerospace.
- **Bedford Working Rating Scale (BWRS)** [94]: The BWRS can be defined as a uni-dimensional rating scale designed to identify the operator's spare mental capacity while completing a task. This scale presents a 10-items scale list to which elaborate descriptions are attached. Users are generally guided through a hierarchical decision tree to narrow down their choices of workload ratings and select a single one in the end (see Fig. 8, extracted from [94]).
- **Workload Profile (WP)** [95]: This methodology involves asking subjects to provide the proportion, typically on a 0 to 1 scale, of the attentional resources they believe they used after completing a task list. This approach seeks to capture the retrospective assessment of how individuals perceive the distribution or allocation of their attentional resources across the various tasks they have undertaken.

All the mentioned instruments were thought as paper-and-pencil tools, as these can stimulate a participatory approach (see [96]) among all the different individuals involved in the assessment process. Rubio et al. [97] conducted an evaluation of several psychometric properties (intrusiveness, sensitivity, diagnosticity, and validity) for three of the multi-dimensional subjective workload assessment instruments. A

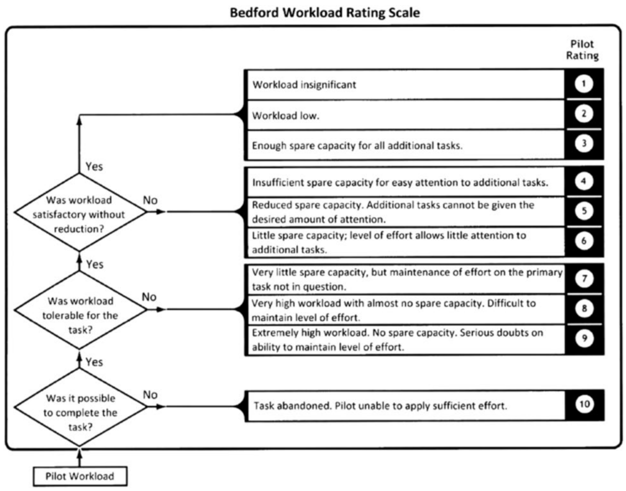


Fig. 8 Bedford Working Rating Scale (BWRS), taken from [94]

special attention was given in the paper to WP tool, which was proved to have an outstanding sensitivity. Although commonly employed for their practical convenience, research has been proving that these techniques can still be subject to some enhancements. Concerning the Bedford scale, for example, this does not provide any information on the time-effort, which is instead an important factor affecting the way pilots feel tolerant about a task. With the so-called Boscomb Down Workload Rating Scale (BDWRS), Ridgway et al. [98] showed a simulator study involving professional pilot to introduce "the ability to differentiate between a short workload spike within a longer task and a moderate but relentless demand for the whole task duration".

An opposite approach for the workload assessment would require the comparison between two or more tasks rather than making absolute judgments. Additionally, the so-called SWORD (Subjective WORkload Dominance) technique was discussed in Refs. [90, 99] and has three main steps. At the beginning, the user is provided with a sheet containing all possible paired task comparisons. S/he indicates, then, which task prevails over the other by filling in a horizontal bar with an odd number of selectors. Subsequently, a matrix is created, with each cell representing the comparison of the task in that row with the task in that column. A final rating is derived from this matrix, providing a measure of the task-related workload on a ratio scale relative to all the other tasks. SWORD can be finally considered a *projective* workload tool, due to the ability of enabling individuals to predict or estimate workload in tasks they have not personally performed. All the instruments discussed so far are based on a cognitive workload self-reminder since they are typically administered just after the completion of a task. Cognitive workload should actually be measured almost in real time when considering a dynamic environment such as a flight mission. Operators may perceive workload differently for various reasons, introducing variability and biases in the interpretation of questions within subjective techniques. Claims were made suggesting that subjective-oriented assessment techniques may be more reflective of the operator's memory than an accurate measure of workload. Also, individuals might often confound mental and physical workload or external demand and the task intrinsic difficulty. Given these challenges, novel objective techniques have emerged, often based on task-related models and/or psychophysiological signals sensed on-board. These objective approaches aim to provide a more accurate and direct assessment of workload, minimizing the influence of subjective interpretation and memory-related biases.

5.1.2 Task-Based Workload models and Multiple Resources

To complement subjective methods, researchers have also developed more objective measures of cognitive workload. Over the years, the aeronautic environment has consistently been acknowledged as a complex workplace where individuals often need to perform multiple tasks simultaneously. One has to consider, also, that beyond the concurrence of multiple actions, decision-making processes also have an impact on the pilot's perceived workload. These latter are associated to all the kind of interruptions that the normal course of action into a mission can have, and that normally leads the pilot to interchange or overlap some tasks. The importance of interruption management has been investigated in several works. These are mostly indicated in the Piera et al.'s research work [47].

One of the most significant classification of workload models can be made, in fact, according to the assumption they make concerning time-sharing performance: a) the single channel [100] model assumes that the pilot can handle only one task at a time.; b) the single resource model [101] recognizes that concurrent task performance is possible even if relying on a limited pool of mental resources; c) the multiple resource model [102] finally proposes that demands may also be offloaded and tasks distributed across the different resources of the operator. According to this model, individuals possess a limited capacity central processor that can allocate its involvement to different channels as the tasks they need to accomplish vary. Wickens' article on the famous Multiple Resources Theory (MRT) [102] made a significant contribution to research on resource management in multi-tasking environments. All human resources can be conceptualized through a series of dichotomous channels corresponding to each stage of mental processing, that are perception, cognition, and response (see Fig. 9). In addition to the inherent demands of tasks, Wickens suggests that a significant contributor to mental workload arises from resource interference between concurrent tasks.

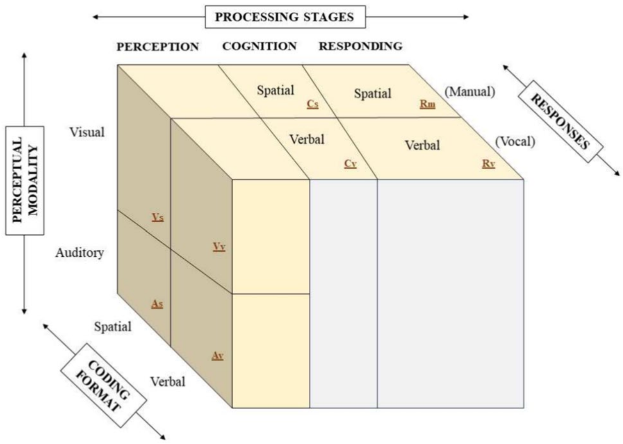


Fig. 9 Multiple-Resource Theory (MRT) schematic visualization as proposed by Wickens [102]

Another notable reference for workload modeling was given in the Sarno's manuscript [103], where the author detailed the description of these three prominent examples:

- **Time Line Analysis and Prediction (TLAP) Model** - Empirically, it has been observed that performance tends to decline when the time required for a task exceeds 80% of the pre-allocated time. Consequently, workload can be calculated as the ratio of the time required to the available time. Notably, this model does not make any assumptions about task competition across channels.
- **Visual Auditory Cognitive and Psychomotor (VACP) Model** - A first distinct workload components and channel separation was done with the VACP Model. For all the components of demand (visual, auditory, cognitive, psychomotor), a vector of demand values must be assigned according to the evaluation scales criteria created by subject matter experts. The average workload can be computed, then, by summing the demands within each component for all the tasks performed at a given time.
- **WL index (W/INDEX) Model** - With this model, there is an explicit calculation of tasks interference, as the assumption that this is proportional to mental workload is valid. To implement the W/INDEX model, a matrix of resource-conflict coefficients is also required, that reflects the degree of interference caused by resource overlap.

A good workload model should be able to make predictions that are highly correlated with empirical measures of performance. Sarno et al. [103], therefore, employed performance data to evaluate the predictive power of the mentioned 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. A way to define the interference between some tasks in the manuscript was 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 and vice versa.

5.1.3 Pilot Health Monitoring

While associating workload with tasks has yielded positive results as for the pilot assistants developed at UBM, all the recent advance in wearable and non-wearable sensor networks research is paving the way to develop a real-time pilot's monitor that would be able to trigger in case of pilot incapacitation episodes. Significant research efforts have focused on exploring the correlation between cognitive workload and human physiological signals. Studies indicate that physiological changes can serve as early indicators of performance decrements in operators, providing valuable insights to prevent accidents. With the right suite of sensors, a digital flight assistant would, therefore, perform real-time classification of the pilot's cognitive state and provide adaptive decision support. A structured sorting of the existing bio-signal monitoring systems for aviation can be found in some literature reviews such as in Refs. [8, 104]. While the aviation industry has expressed interest in several sensors for detecting pilots' stress levels, research in the pilot monitoring field is still at an early stage, so that more efforts will be required to establish robust correlation models. Various medical wearable devices have been already employed also in the context of aviation (see Table 4).

Despite the rapid evolution of pilot monitoring technology in aviation, several challenges still need to be addressed for these technologies to become firmly established.

- **Reliability and Accuracy**: Wearable sensors need to provide reliable and accurate measurements to ensure the validity of the collected data. All sensors must be capable of delivering consistent and precise readings under various environmental conditions and during the different phases of a flight. A major aspect to cope with will be to take into account that stress is a multifaceted construct and that it normally gets influenced by various individual and situational factors. 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. Artificial Intelligence is envisaged to undertake these challenges.
- **Sensor Integration and Compatibility**: Integrating wearable sensors into the existing pilot equipment and cockpit avionics systems can be complex. To avoid signal contamination, a sensor network approach will be essential. Various methodologies and techniques can be used when pursuing this approach, as reported in Ref.

Table 4 Some notable wearable sensors eligible for stress detection in aviation

Sensor Type	Description and Employment
Electrocardiography (ECG)	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 [105] and physiological arousal
Electrodermal activity (EDA)	An EDA sensor, also known as a galvanic skin response sensor, detects variations in the skin's electrical conductance, which correlates with sweat gland activity [106]. Elevated EDA levels are typically associated with activation of the sympathetic nervous system, signaling stress or emotional responses
Electromyography (EMG)	EMG sensors detect muscle activity and can identify patterns of muscle tension or relaxation. One of the most recent signals to have been explored is facial electromiography (fEMG), which describes the way some magnified measurements can serve as indicators of cognitive workload [107]
Electroencephalography (EEG)	EEG sensors measure brainwave activity by detecting electrical signals emitted from the scalp. An elevated cognitive workload, in this perspective, has been often associated with an increase in the theta-band power and a decrease in the alpha-band power of such signals [108, 109]. Aricò et al. [110] developed an online Mental Workload classifier based on the use of EEGs. Other studies, on the other hand, focused on some specific features of these sensors' response. Dorneich et al. [64], for instance, claimed the P3 Event-Related Potential can be seen as a biomarker of cognitive decline [89]. The P3 is an EEG-evoked positive peak at around 300 ms which can be observed during visual or auditory working memory tasks
Photoplethysmography (PPG)	Similarly to ECGs, PPG sensors measure HRV and changes in the blood volume and blood flow just using light [111]. Compared with ECGs, PPG sensors can be more easily employed for shrinking into wearable devices (e.g., smartwatches)
Functional Near-Infrared Spectroscopy (fNIRS)	fNIRS employs near-infrared light to detect fluctuations in oxygenated and de-oxygenated hemoglobin concentrations in the prefrontal cortex, providing an indirect measurement of brain activity [112]
Eye-tracking	Some eyes-related parameters, such as fixations, blink rate, or saccades, can serve as indicators of workload measurements. Glasses or commercial camera-based video recording systems are typically employed for this purpose. McDuff et al. [113] demonstrated the use of a five-band digital camera to detect cognitive stress by observing pilots' facial landmarks. Similarly, Honecker [7] employed multi-camera systems for the recognition of visual areas of interest based on the pilot's gaze tracking

[114]: (a) independently estimating cognitive states from each sensor and then fusing these estimated; (b) performing a cognitive state estimation based on a fused pool of extracted features from each sensors (that is the base of data fusion techniques); (c) using data from one or more sensor to extract more/different information from another sensor and/or for sanity checks. Up to the present progress, each of these approaches may have pros and cons; however, the important topic that remains open will be the optimal choice of the smallest and most significant number of physiological indicators to enter such a sensors network for calculating mental workload.

- **Standardization and Validation**: It is essential to establish standardized validation protocols and procedures for wearable sensors in aviation. Consistent measurement methodologies, calibration procedures and data analysis techniques need to be developed and agreed upon to ensure interoperability and comparability between 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 put in place.
- **User Acceptance and Comfort**: Wearable sensors should not impede pilots' comfort, mobility, or performance. Sensors should be ergonomic, lightweight, and non-intrusive to minimize distractions and maintain the optimal pilot functioning, as it is for current consumer electronics. Various efficient devices have been developed for this purpose, including energy-harvesting arm devices [115] or smart shirts. A wireless, fully wearable wristband was reported, for example, by Maiolo [116] for the pilot's cardiac activity detection.

5.2 Pilot Incapacitation

One of the crucial aspects to consider for enabling Single-Pilot Operations is how to manage in-flight pilot incapacitation episodes. According to the definition given by in the ICAO's Manual of Civil Aviation Medicine, in-flight incapacitation can be "any reduction in medical fitness to a degree or of a nature that is likely to jeopardize flight safety" or even as "any physiological or psychological state or situation that adversely affects performance". Usually, incapacitation is attributed to various medical conditions, including hypoxia (oxygen deficiency), cardiovascular and gastrointestinal diseases, acute pain syndromes, or other conditions such as headaches, dizziness, and the so-called Spatial Disorientation (SD). On the other hand, an incapacitation episode can also occur outside the medical context, for example whenever fatigue, stress or distraction contribute to affect pilot performance. Going back to the virtual associate systems developed for the militarizes [79], for example, the pilot incapacitation was not strictly documented as a medical condition but rather viewed as the consequence of any significant deviation from standard operating procedures. Certain environmental factors, such as extreme weather conditions or in-flight emergencies, can also create situations in which pilots may struggle to maintain control of the aircraft, resulting in a partial incapacitation that must still be detected. A potential scheme of the way to formalize an assistance system in order to let it monitor and detect possible incapacitation states of the pilot is given in Fig. 10.

Extensive research has been ongoing to collect data on the medical state of pilots and document incidents and accidents related to incapacitation. This is fundamental for airlines in order to adjust their training policies and internal checks on the work of pilots. So far, incapacitation events have rarely been associated with fatal accidents. DeJohn et al. [117], for example, provide a technical report for analyzing cases of in-flight medical incapacitation in the U.S. airline pilots in the six years going from 1993 to 1998. A frequently cited cause of incapacitation for these pilots was acute gastroenteritis during the cruise phase. Overall, the joint rate of impairments/incapacitations was lower than 0.050 per 100,000 h of flight. One potential reason supporting this is that active pilots are generally considered to be healthier than the general population [118]. This is due to stringent employment selection processes and regular medical assessments required for maintaining the license. Similar analyses were conducted in Ref. [119], where the aim was instead to define the annual rate of incapacity of UK commercial pilots. A 0.25 % rate was computed for the year 2004. The same manuscript has also outlined the annual male incapacitation rates divided by age groups, which created new evidence in favor of the measurable age-dependent increased risk of incapacitation. Since the reporting to airlines is not mandatory, however, one has to consider that possible incapacitation episodes can always be omitted when these never led to a problem on flight.

Within the large number of scenarios analyzed, what emerges especially in the reconstruction of the selected flights in the study of DeJohn et al. [117] is that where a medical impairment threatened to jeopardize the mission objective, the role of the remaining pilot proved crucial in recovering the flight and/or making an emergency landing. Current standard operations, as said, normally involve both pilots undergoing cross-checks to monitor one another with observations and communications. According to ICAO, the “two-communication” rule has to stand, that is flight crew members should always have a high index of suspicion of a ‘subtle’ incapacitation any time a colleague does not respond appropriately to more than two verbal communications.

While stricter medical requirements for pilots can certainly contribute to mitigating the risk of in-flight incapacitation, relying solely on these measures may not be sufficient to ensure safety. While the frequency risk of impairments may be relatively low, in fact, the potential hazards this pose to the flight safety can be serious for SPOs. Given the critical role that the pilot will have on a single-crew flight, robust strategies and protocols must be determined to detect any subtle or clear signal of impairment. One of the key issues in this regard is to detect the incapacitation relying on the recorded physiological parameters of the pilot, as well as determine the appropriate assistance after that. As the most effective approach to think of, researchers are envisaging

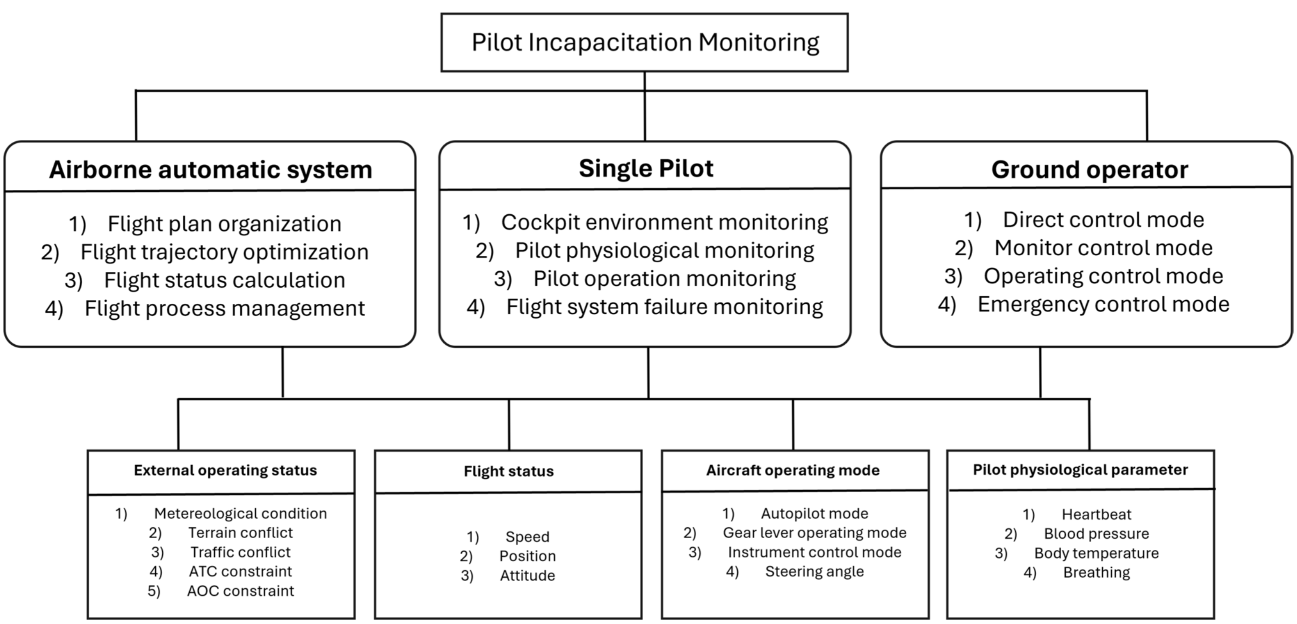


Fig. 10 Pilot incapacitation monitoring architecture. Adapted from Wang et al. [120]

to proactively characterize incapacitation through specific markers for automation. As the reader can see in Ref. [121], the current paradigm is to set up pragmatic and direct way of thinking to recognize each physiological "failure mode" through the detection of certain characteristics from physiological sensors. The authors in Ref. [121] proved that each pilot's physiological failure mode can, therefore, be expressed as a collection of physiological signals. Apart from this, also establishing effective communication channels and protocols for alerting ground personnel or other airborne assets will be essential for timely intervention and assistance.

To this purpose, Schmid and Stanton [41] proposed a detailed design concept on how the detection and the subsequent recovery from an incapacitation should be in the context of a reduced-crew cockpit. This work suggested that implementing an autoland procedure on-board would be necessary for remote assistants to manage incapacitation scenarios effectively. One subtle and very rare case of incapacitation the paper is also trying to model in the systems theoretic approach is homicide-suicide, that is intimately connected to mental health. Given the low technical maturity on assessing these aspects, the authors in Ref. [41] argued that it should be the aircraft systems' automatic procedures to detect potential hazards associated with unauthorized inputs. Overall, it is important to note that the research in this area is currently limited to systems theoretic models, and the predictions for incapacitation have not yet been empirically validated.

5.3 Artificial Intelligence in Aviation

Contributions from the literature still lack a definitive analytical framework describing 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 [53], even cultural considerations shall be considered, since individuals with various educational backgrounds may react differently to external stimuli. Constructing a person-independent classifier would, therefore, be ideal. Several studies [122, 123] investigated the feasibility of Machine Learning models (ML) in order to classify mental workload across different subjects. AI comes into play, indeed, for its intrinsic capacity of processing huge amount of data, which could be the case of the sensors needed for pilot health monitoring, as well as for all advanced automation applications involving the general concept of human-AI teaming. Overall, AI can be a game-changer for different sub-sectors in the upcoming future of commercial aviation, since its capability of (i) providing valuable support to the crew by delivering critical situation forecasts, (ii) reducing the workload or air traffic control operators through improved predictions of traffic behavior, (iii) supporting the optimization of flight routes to reduce flight time, fuel consumption, or (iv) being integrated with airport security systems such as screening, perimeter security and surveillance. A comprehensive list of the main AI-based solutions designed for aviation can be found by reading the recent report "FLY AI Report Demystifying and Accelerating AI in Aviation/ATM", prepared by the High Level Group on European Aviation AI.

A significant contribution has been provided by the European Aviation Safety Agency (EASA), which recently established an internal task force entirely dedicated to the topic of AI. Specifically, the production of a comprehensive action plan has been entrusted to the Agency through conceptual guidance deliverables. According to the Artificial Intelligence Roadmap guidelines [12, 13], the safe and reliable integration of AI in aviation will consist of going through three levels of applications, which are human assistance (Level 1 AI), human-AI teaming (Level 2 AI) and advanced automation (Level 3 AI).

AI essentially defines, indeed, the boundary between automated and so-called autonomous systems. An autonomous system has the ability to determine a course of action among several alternatives and to adapt itself to situations that have not been predetermined. Single-Pilot Operations, in this sense, could be considered exactly in between these two opposing concepts, since the requirements generally call for scalable autonomy depending on the state of the pilot. An AI-based system could in fact help reducing the pilot's authority on the flight especially while managing high-level tasks. Within the first published deliverable of the EASA AI Roadmap, which is called "Guidance for Level 1 & 2 Machine Learning Applications" [124], an introductory use case for a virtual a co-pilot has been proposed. A list of the capabilities that a Level 2 AI aiding system should have to support the end-user's job can be inferred when overlapping the requirements induced in these guidelines with the previous literature. As main features, the system must (a) interact through a speech and gesture interface with the pilot, (b) adjust task allocation and share decisions with the human counterpart, (c) be able to perform identification and management of an on-board failure, (d) continuously monitor the aircraft system states and data link with the ground, and (e) follow pilot activities to detect and specify all the missed and partially completed tasks.

At the same time, the integration of AI-based systems on aircraft can expose them to novel external threats in the communication infrastructure. A so-called data poisoning occurs, for instance, when the potential attacker is able to access the model training dataset by injecting erroneous data and thus make it learning something it should not. Communication is also a matter of social issues inside the cockpit, as the absence of the FO might lead the single pilot in confusion or in a boredom status. When the other entity is an autonomous one such as for an AI-based system, humans can be highly influenced by superficial aspects, such as their apparent gender, humanness, politeness, and personality. Also, users coming from different technical or cultural [125], or linguistic, backgrounds can have widely varying mental models of how AI systems work.

Currently, developing an AI-based virtual flight assistant is widely recognized as one of the most challenging endeavors to face with for enabling SPOs. Achieving effective training for these type of assistants, on the other hand, can pose challenges due to the complexities associated with accessing authentic flight data. Since this limitation, the idea of gathering users' expertise has been investigated to develop a machine learning based assistant. An example might be found in the outcome of the European project HARVIS (Human Aircraft Roadmap for Virtual Intelligent System). What is behind HARVIS is a rule-based Expert System that is built upon the expertise of professional pilots. Such a system would in fact require pilots to tag and classify a large number of recorded scenarios to form the internal situational knowledge of the assistant. As illustrated in Fig. 11, the assistant undergoes a training phase through this labeling process to extract the essential rules for providing real-time support in decision-making. Two single-pilot use cases were identified as most deserving of assistance. At first, an assistant was set up for helping pilots during the process of executing a stabilized approach [126], particularly in the decision-making regarding whether to initiate a go-around or not. Another scenario involves the dynamic rerouting of the flight [127] when an abnormal situation occurs. A validation session was performed for testing the HARVIS capability for both the use cases, involving professional pilots at the A320 Aeronautical Human Computer Interaction platform (ACHIL) at ENAC.

6 Conclusion

The single-pilot operations concept is expected to offer cost efficiency and to tackle the challenges of the limited pilot supply which is predicted for the next future. According to the most recent schedule outlined by EASA, a viable single-pilot solution for large commercial airliners and ATM operations is projected to be attainable by the mid-2030 s. A critical point for discussion, however, is that the transition to SPOs will require a comprehensive overhaul of certification methods regarding human-AI teaming. All regulations on the topic will have to consider the shift from systems operating solely on deliberative or reactive principles to those incorporating diverse levels of autonomy. Just introducing artificial intelligence functions, for instance, is forcing all the stakeholders to take actions to prevent the development of dangerous applications that may violate fundamental human rights. Also, the complex organizational structure which is foreseen for SPOs will ensure that ground staff will also be subject to appropriate regulation.

The main objective of the present scoping review has been to provide insights into the current state of research on SPOs, doing this by taking different points of view across macro topics in the context of a very wide subject. Our goal has been to select key areas of interest that can be further explored within the context of transitioning to SPO. This review can serve to shed some light on topics that are often fragmented at a subsystem level. Our aim has been to emphasize where possible the gaps and potential directions for future research. What emerges is that enabling SPOs necessitates substantial changes in current operational frameworks, entailing the establishment of new roles and responsibilities alongside the reconfiguration of the existing ones. Automation will be pivotal in this process, requiring a redesign of interfaces on the flight deck to facilitate seamless integration between operators and systems. An intriguing concept expected to emerge from SPOs is the Digital Flight Assistant (or cognitive assistant), which will provide support to the single pilots

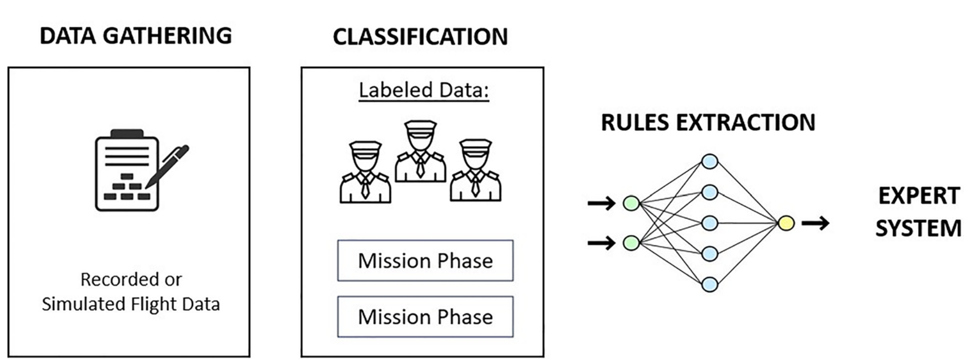


Fig. 11 Potential application schematic for an AI-driven digital assistant making use of recorded flight data.

based on their detected workload. Up to now, there are still few examples of workload-adaptive assistants and the most important heritage comes from the military domain. A growing consensus for the civil counterpart, however, has been developing in these years thanks to AI-based assistant concepts. The future evolution of these systems will depend on the accessibility of government-held data for training purposes as well as the establishment of non-intrusive, efficient pilot monitoring techniques.

A significant portion of the technology required for SPOs is either being developed or is already accessible. However, concerns have been raised by pilots' unions regarding the management of safety issues associated with SPOs and the societal acceptance of this approach. A crucial driver for the future implementation of SPOs will be the ongoing involvement and support of pilots' feedback throughout the design phases. This involvement can greatly improve outcomes and promote greater public trust in autonomous systems. At present, the main challenges hindering SPO development largely stem from the Human Factors perspective. One of the primary challenges will be to ensure the highest level of safety for passengers while preventing excessive workload on pilots as they adapt to new procedures and standards.

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Data Availability Data sets generated during the current study are available from the corresponding author on request.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

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